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Journal of Sedimentary Petrology

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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Among papers to appear in forthcoming issues of the *Journal* are the following:

Cemented sandstone slabs of the Chandeleur Islands, Louisiana. By J. P. Morgan and R. C. Treadwell.

Roundness and shape of marine gravels from Urk (Netherlands), a comparison of several methods of investigation. By Tj. H. van Andel, A. J. Wiggers, and G. Maarleveld.

A new teaching and research aid in sedimentation. By D. J. Jones.

Heavy minerals of Jacksonian sediments of Mississippi and adjacent areas. By Ming-Shan Sun.

Sedimentary framework of the modern Mississippi delta. By H. N. Fisk, C. R. Kolb, E. McFarlan, Jr., and L. J. Wilbert, Jr.

Testing graphical methods of grain-size analysis of sandstones and siltstones. By R. A. Cadigan.

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FIGS. 1–11, MARCH, 1954

THE TETRAHEDRON AS A FACIES MAPPING DEVICE

W. C. KRUMBEIN
Northwestern University, Evanston, Illinois

ABSTRACT

The geometry of the tetrahedron and of points on and within it are examined in terms of their application to facies maps. It is shown that any interior point may be projected in five different ways on each of four faces. In addition to point projections, the tetrahedron may be sliced along percentage planes, ratio planes, or combinations of the two to provide facies classes within the tetrahedron.

Maps based on such tetrahedral segments present four end members directly. Projections on selected faces provide the basis for some current facies maps, but additional possibilities for "projection facies maps" can be explored by using other projected points. Several experimental maps of the same data are presented to indicate different ways in which maps may be designed to emphasize various characteristics of stratigraphic units.

INTRODUCTION

The end member tetrahedron, widely applicable to sedimentary rock classification (Pettijohn, 1949) has also been applied in principle to facies mapping. More commonly one of the triangular faces or a tetrahedron edge is used in map design. Examples include the sand-shale-lime triangle as a three component system and sand-shale as a two component system.

Triangles have proved their usefulness where three end members provide a logical subdivision of stratigraphic units. Numerous occasions arise, however, in which four end members are necessary for complete analysis of the section. An example is the study of mixed units having limestone and evaporite as well as sand and shale.

The clastic ratio was defined (Krumbein, 1948) as the ratio of sand plus shale to limestone plus evaporite. The limestone and evaporite were combined into a single end member. As long as no evaporites are present, this leads to the simple sand-shale-lime triangle. When evaporites are abundant, however, the clastic ratio fails to differentiate the two classes of non-clastics. A partial solution to this problem was offered by Andrichuk (1951) in his evaporite triangle, in which sand and shale are combined into one end member, leaving separate end members for limestone and evaporite. As long as the clastics are dominantly shale, or where no distinction between shale and sand is needed, this triangle serves an important purpose. Again, however, where all four lithologies are important, any three end member system is inadequate for full analysis.

Relations between the two triangles and further extensions in use of combined end members can be visualized by considering the triangles as adjacent faces on a tetrahedron. Moreover, if a single map is to be designed for displaying all four end members, the relations among the rocks can best be seen by treating them in the three dimensional framework of the tetrahedron.

The purpose of this paper is to review some of the geometrical properties of points within and on tetrahedra, to show how they are related to various planes and projections, and to demonstrate that problems of designing facies maps for two, three, or four end members can be integrated by treating them as particular aspects of the tetrahedron. In developing this paper the writer is indebted to his colleagues at Northwestern University, notably Dr. A. L. Howland, who suggested several of the relations used here. Dr. Charles Ryniker and E. L. Herbaly,

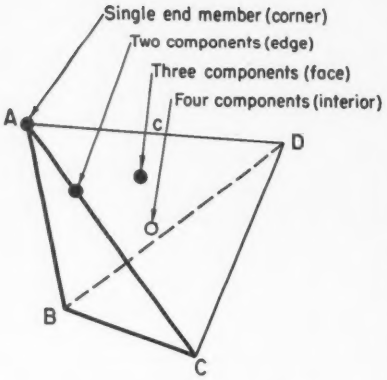

FIG. 1.—Points on and within a tetrahedron.

of the Gulf Oil Corporation, Tulsa, have discussed many of the problems with the writer and have read the manuscript.

GEOMETRY OF THE TETRAHEDRON

Some aspects of the geometry of tetrahedra are treated by Mertie (1948, 1949) in connection with plotting five or more variables on hypertetrahedra. The following development is based partly on Mertie's papers.

Figure 1 shows a tetrahedron with four corners labeled from A to D, representing any four end members. When only a single end member is present, as in a section with 100 per cent limestone, the data plot as a point at one of the corners. If two end members are preesnt, such as sand and shale, the point falls along one of the tetrahedron edges. Three end members plot as a point on a triangular face, and four end members plot as a point within the tetrahedron.

The four coordinates which locate a point within the tetrahedron may be called a, b, c, and d, where each letter expresses the proportionate distance along an axis leading from the center of the opposite face to a given vertex. The necessary condition is that $a+b+c+d=100$ per cent. In facies work the coordinates are all positive, although negative coordinates may occur geometrically.

For the ACD triangle (called a *trigon*) the condition for a point being located on the face is that $b=0$, so that $a+c+d=100$. For the point to fall along the AC edge, both b and d must be zero. Finally, for the point to fall at A, the condition is that $a=100$.

Any point within the tetrahedron may be projected on any of the faces by appropriate transformations. For example, in figure 2 a line from corner A may be projected through point P to the opposite face BCD. The projected point so located is here called the *trilinear point*, TR, and its coordinates on face BCD are found by recalculating the b, c, and d values to 100 per cent. In similar fashion, point P can be projected onto any of the other faces.

A second projection of point P on face BCD is accomplished by dropping a perpendicular from P to the face, as in figure 2. The intersection of line and face is called the *orthogonal point*, OR, and its coordinates on the BCD face are $(b+a/3)$, $(c+a/3)$, and $(d+a/3)$. Orthogonals can also be projected onto the other three faces from P.

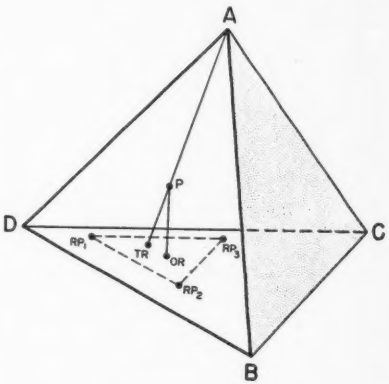

FIG. 2.—Tetrahedron with ABD face removed to show relations of interior point P to its projections.

A third kind of projection of point P on face BCD is accomplished by combining two of the coordinates, as is commonly done in facies work. For example, if a and d are combined, a projected point is located on the BCD face with coordinates $(a+d)$, b, c. Similarly, two other projected points can be located on the same face by combining $a+b$ and $a+c$. These are here called *ratio points*, *RP*, because of their common use in plotting ratio values on facies triangles. Figure 2 shows the three ratio points, which themselves define an equilateral triangle on face BCD.

The relations among the several projected points can be seen from an example. Consider a stratigraphic section with the following end members:

TABLE 1.

A (limestone),	$a=$	40%
B(sandstone),	$b=$	10
C (shale),	$c=$	20
D (evaporite),	$d=$	30
		100%

This point falls within the tetrahedron. To find its several projections on face BCD, as shown in figure 3, first locate the trilinear point by recalculating $b+c+d$ to 100 per cent. The sum of the three is 60, and the recalculated percentages are $b=17$, $c=33$, and $d=50$. This point is labeled TR in figure 3. Next locate the orthogonal point OR by adding $a/3$ to each of the other coordinates: $b+a/3=10+13=23$, $c+a/3=33$, and $d+a/3=44$. The three ratio points are found by combining b, c, and d with a in successive points: $a+d=70$, $b=10$, $c=20$. This point is RP_1. The other two points are $a+b=50$, $c=20$, $d=30$; and $a+c=60$, $b=10$, $d=30$. The three ratio points are connected by lines which define an equilateral triangle. The triangle may also be constructed by plotting the absolute values of b, c, and d on face BCD.

In the assignment of facies end members in this example, RP_1 is the point commonly plotted on the facies triangle when sand (b), shale (c), and lime+evaporite ($a+d$) are the end members. Hence, the clastic ratio line, CR, extends through point RP_1, parallel to the BC edge. Moreover, the trilinear point lies on a line which connects D and RP_1. This line is the sand-shale ratio line, SsR. Lastly, the orthogonal point OR lies at the center of the triangle defined by the ratio points, and the size of the triangle is equal to the percentage of the missing end member, a, here 40 per cent.

If similar operations are performed on the other three faces, the point P within the tetrahedron is represented by 20 projections on the tetrahedron surface. Any of these projected points may be used in the design of particular facies maps; as mentioned, one of the ratio points is commonly so used.

PLANES WITHIN THE TETRAHEDRON

The clastic ratio and sand-shale ratio lines of figure 3 represent traces of planes within the tetrahedron. Figure 4 shows a developed tetrahedron with its four faces, obtained by cutting the solid along the AB, AC, and AD edges. The point P of the foregoing example is shown in projection on the four faces in terms of TR, OR, and three RP points. The clastic ratio line, $(b+c)/(a+d)$ passes through RP_1 and is parallel to the BC and AD edges. The sand-shale ratio line, b/c, lies on the ABC and BCD faces; and the evaporite ratio line, d/a, lies on the ABD and ACD faces. These lines always pass through RP_1 and TR, and they represent intersections of interior planes with the tetrahedral faces. Except for RP_1 the ratio points are numbered independently on each face, using BC and AD as base lines. This convention and the reversal of face BCD in figure 4 changes the subscripts on points RP_2 and RP_3. A different notation would be required if the geometry of the points on related faces were developed.

The upper four diagrams of figure 5

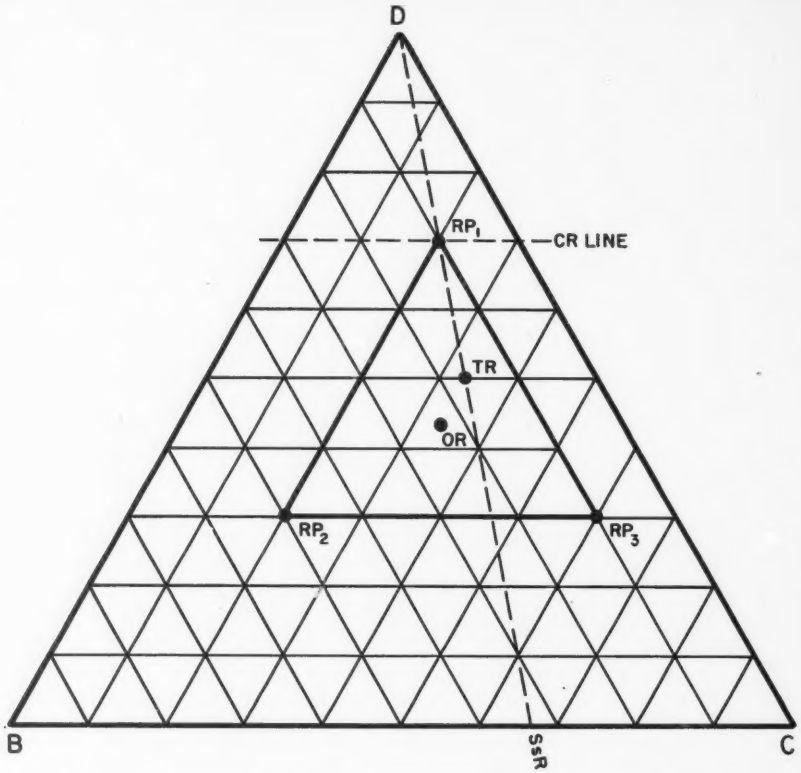

FIG. 3.—*BCD* face of tetrahedron, showing projections of point *P* from table 1. Projection as viewed from within tetrahedron.

show the foregoing planes in perspective within the tetrahedron. The right center diagram shows the planes intersecting at point *P*. Along these planes and their lines of intersection the corresponding ratios are constant, with values $CR=0.43$ $SsR=0.50$, and $ER=0.75$. It may be noted that the clastic ratio plane is a rectangle whereas the others are triangles.

The relations of the projected points to the planes in figures 4 and 5 indicate that RP_1 is projected to the *ABC* and *BCD* faces along the intersection of the clastic ratio plane and the sand-shale ratio plane.

In addition to planes defined by ratios, percentage lines on the triangular faces also define triangular planes which cut the tetrahedron parallel to each face. The lower diagrams in figure 5 show a tetrahedron with an "*a*-percentage" plane, and one with percentage and clastic ratio planes intersecting. The clastic ratio line may coincide with a percentage line on a tetrahedral face, but the clastic ratio plane is inclined to the percentage plane at an angle, as shown in the lower right diagram of figure 5.

The occurrence of planes of various sorts within the tetrahedron permits an-

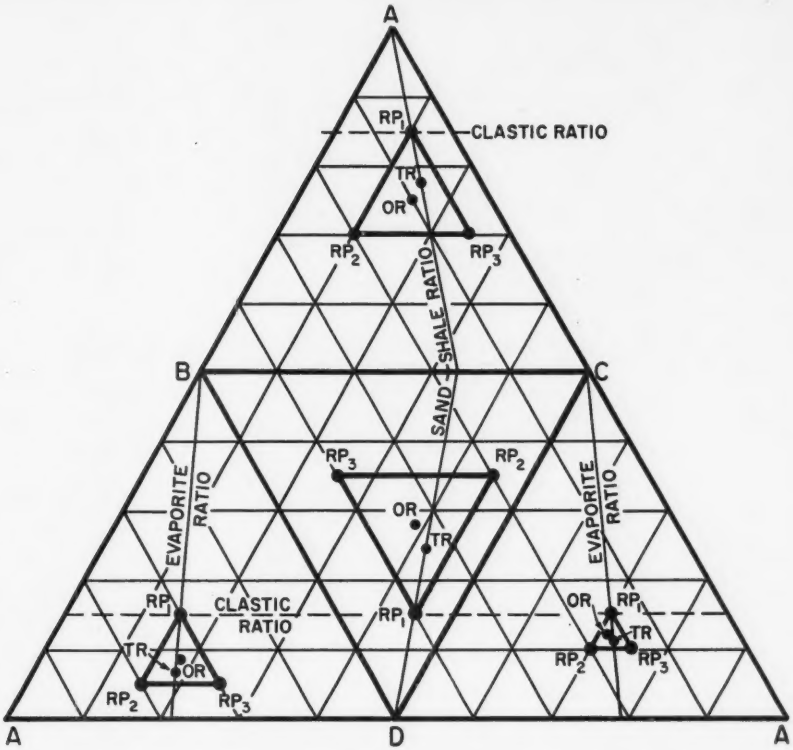

FIG. 4.—Developed tetrahedron, with 20 projections of point P from table 1. Faces viewed from outside of tetrahedron.

other approach to the problem of facies mapping of four end members. Instead of mapping the projections of interior points on selected faces, the tetrahedron itself may be sliced along selected planes to provide three-dimensional subdivisions of the solid, each of which may contain a "facies population." Several methods of slicing, involving ratio cuts, percentage cuts, or combination ratio-percentage cuts are possible. Figure 6 shows three developed tetrahedra with perspective sketches. The first is cut along the clastic ratio (laid off along AB, AC, BD, and CD), the sand-shale ratio (laid off along BC), and the evaporite ratio (laid off along AD). The second is cut at the 50 per cent planes on each face. The third tetrahedron is cut on the clastic ratio planes (laid off along AB, AC, BD, and CD), the sand-shale ratio (laid off along BC), and along percentage planes on the d axis. The percentage cuts show up on the ABD and ACD faces.

The number of slices depends upon the detail desired; figure 6 merely illustrates the forms of the resulting solids. It is worthy of note that the percentage slice provides four corner tetrahedra and a central octahedron, all with edges of the

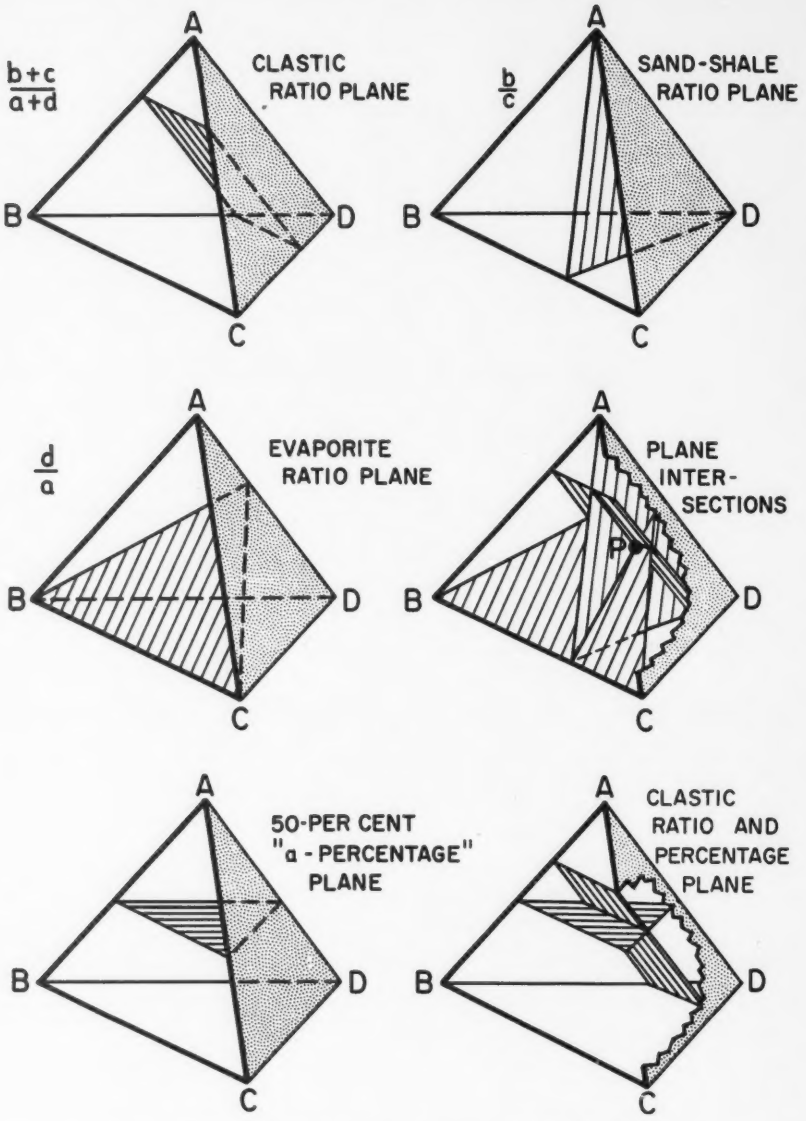

FIG. 5.—Tetrahedra with *ABC* faces removed to show interior planes.

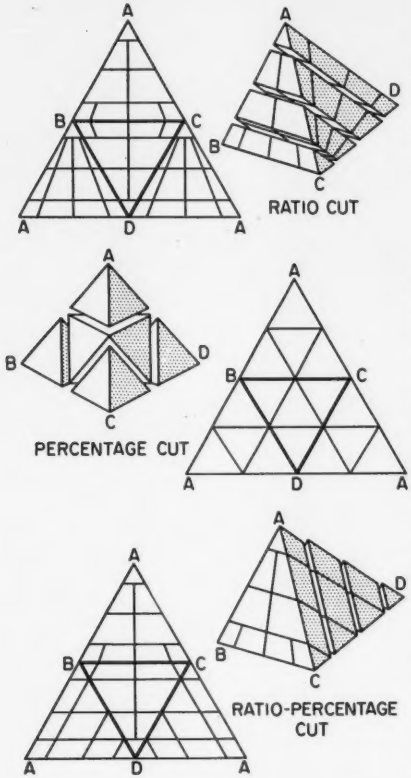

FIG. 6.—Developed and perspective views of sliced tetrahedra.

same length, if the cut is made at the 50-per cent planes.

Lines and planes associated with the tetrahedron or its faces may be expressed as equations in trilinear or quadriplanar form, or they may be converted to Cartesian coordinates (Mertie, 1948). Hence, it is possible to investigate the mathematical relations among the planes described.

APPLICATIONS TO FACIES MAPPING

For completeness of presentation, this paper will include two, three, and four end member systems for facies mapping. In this manner the increasing complexity of the problem, and the larger variety of techniques associated with more end members can be brought out. It is assumed throughout that an appropriate isopach base is available for each kind of facies map.

Two End Members

Maps based on two end members, A and B, with coordinates $a+b=100$, are relatively straightforward, and in their ratio form they may be expressed as b/a or a/b. Inasmuch as all such points lie along an edge of the tetrahedron, which is equivalent to a side of one of the triangular faces, a simple bar legend may be used. The bar may be divided into arithmetic or geometric units, depending on the range of values present or on the occurrence of clusters of values.

Two end member systems may be based on lithology (sand and shale, limestone and dolomite, etc.); on faunal groups (two types of fossils, planktonic vs. nektonic forms, etc.); on environmental groupings (open vs. restricted circulation, shallow vs. deep water, etc.); or on other bases. If percentages are used directly, instead of ratio, two sets of percentage lines may be superimposed and colored according to a preselected scheme. Percentage maps of a single lithologic component (Low, 1951) may be considered as single end member systems.

Three End Members

Three end members systems lead to the familiar 100 per cent triangle with corners A, B, C, and coordinates a, b, and c, where $a+b+c=100$. Three end members permit development of six ratios involving all three end members, and six ratios involving pairs. The three end member ratios are $a/(b+c)$, $(b+c)/a$; $b/(a+c)$, $(a+c)/b$; and $c/(a+b)$, $(a+b)/c$. The two end member ratios are b/a, a/b; a/c, c/a; and b/c, c/b. In both sets the pairs between semicolons are reciprocals, and the choice of ratios depends upon the end

members selected for numerator and denominator.

Two ratios are selected in most three end member systems, one involving all three end members, and the other two. The familiar sand-shale-lime and shale-lime-evaporite triangles belong here when no fourth end member is present. When the triangle is adapted to four end member systems, it is necessary to combine two end members into a single composite, as is done when the fourth end member d is added to a, b, or c. This adaptation is discussed more fully below.

If the two ratios selected are $(b+c)/a$ and b/c, the face involved is ABC, and the ratio lines will always have a fixed geometry. That is, the first ratio plots on the triangle as a family of straight lines parallel to the BC edge, and the b/c ratio plots as a series of lines converging at A. The generalization derived from this is that in any three way ratio, the lines plot as though they were percentage lines of the single end member (A in this case), and the two way ratios plot as diverging lines from the 100 per cent point of the third end member, also A in this case.

The relation between ratio and percentage lines on the triangle, and the fixed geometry of three end member systems is mentioned elsewhere (Krumbein, 1948, 1952). The following equations permit transformations from ratios in the common clastic ratio and sand-shale ratio triangles when no evaporite is present:

$$\% \text{ Limestone} = 100\left(\frac{1}{CR+1}\right)$$

$$\% \text{ Shale} = (100 - Ls)\left(\frac{1}{SsR+1}\right)$$

$$\% \text{ Sand} = (\text{obtained by difference})$$

In these equations, CR is the clastic ratio, SsR is the sand-shale ratio, and Ls is per cent limestone. These equations can readily be generalized in terms of the letters a, b, and c.

Subdivision of the ratio triangle into mapping units is accomplished by selecting limiting values of the two ratios, which establishes areas on the triangle, each representative of a certain "facies population." A conventional subdivision is shown in Krumbein and Sloss (1951, p. 274). The subdivisions used in the evaporite triangle are given by Andrichuk (1951). The choice of limiting values is determined in the conventional case by ease of comparing many maps prepared on the same basis. For specific studies the limits can be arranged according to clusters of points within the triangle.

In ratio mapping two sets of contours are superimposed on the isopach base. In contrast to this, percentage maps may be prepared by plotting the a, b, and c values directly at the control points, and contouring each coordinate separately. The triangle lends itself well to this method, although the maps become more complex in that three sets of percentage lines are required. In any event, facies classes can be defined by certain limiting percentage values.

If one or more end members of three member systems are absent at a control point, the points involved fall either along a side of the triangle or at one of its corners. All points in three end member systems lie on the tetrahedron surface, and it is not necessary to consider point projections or tetrahedral planes in mapping three and member systems.

Three end member systems can be applied to a wide variety of mapping problems. In addition to conventional regional maps, triangles based on specific lithologies, on faunal groups or assemblages, on environmental classes, or on tectonic associations, may be prepared. In each instance the several possible ratios can be defined on the same geometrical basis as discussed here, and named appropriately for the end members present.

Four End Members

Four end member systems include points which lie within the tetrahedron. Individual control points may have one or more components missing, in which case they fall on the tetrahedron surface.

TABLE 2.—*Coordinates of hypothetical sections.*

Point	Limestone (*a*)	Sandstone (*b*)	Shale (*c*)	Evaporite (*d*)	Clastic Ratio	Sand-shale Ratio	Evaporite Ratio
1	100	0	0	0	0	—	0
2	85	0	0	15	0	—	0.17
3	50	0	0	50	0	—	1.0
4	0	0	0	100	0	—	∞
5	65	5	5	25	0.11	1.0	0.68
6	25	5	5	65	0.11	1.0	2.6
7	75	10	5	10	0.18	2.0	0.13
8	10	5	10	75	0.18	0.5	7.5
9	50	15	5	30	0.25	3.0	0.60
10	30	5	15	50	0.25	0.33	1.7
11	15	5	15	65	0.25	0.33	4.3
12	70	15	10	5	0.33	1.5	0.07
13	5	10	15	70	0.33	0.67	14.0
14	5	5	25	65	0.43	0.2	13.0
15	45	20	15	20	0.54	1.33	0.44
16	20	15	20	45	0.54	0.75	2.3
17	55	35	5	5	0.67	7.0	0.09
18	5	5	35	55	0.67	0.14	11.0
19	40	30	15	15	0.82	2.0	0.37
20	15	15	30	40	0.82	0.5	2.7
21	40	50	10	0	1.5	5.0	0
22	20	30	30	20	1.5	1.0	1.0
23	5	10	50	35	1.5	0.2	7.0
24	30	50	20	0	2.3	2.5	0
25	20	70	10	0	4.0	7.0	0
26	15	50	30	5	4.0	1.67	0.33
27	10	30	50	10	4.0	0.6	1.0
28	5	10	70	15	4.0	0.14	3.0
29	0	100	0	0	∞	∞	—
30	5	75	20	0	19.0	3.8	0
31	5	55	40	0	19.0	1.4	0
32	5	20	75	0	19.0	0.27	0
33	0	0	100	0	∞	0	—

Mathematically this means that the point coincides with its projection. For example, by referring back to figure 2, it is evident that when point P has no a-component, it will lie on the BCD face, and the five projected points will merge into a single point.

Three general approaches are available for mapping four end member systems. In the first, two end members are combined into a composite end member, which in effect projects all central points to a selected face along the intersection of the clastic ratio and sand-shale or evaporite ratio planes. This is the familiar sand-shale-lime-evaporite case, and the projected point is RP_1 of figure 3. For special purposes RP_2 or RP_3 may similarly be used.

The second mapping method involves slicing the tetrahedron along appropriate planes, as shown in figure 6, and using each block of the tetrahedron as a facies class or population. The third mapping approach is based on the use of the trilinear or orthogonal projections of the interior points. This leads to the concept of special "projection facies maps," which will be illustrated by use of trilinear projection maps.

The writer is not aware that all three of these methods have been treated in the literature. They are discussed here to indicate some of the possibilities opened by tetrahedron slices and point projections. Several experimental maps are used to show how the same group of points distribute themselves on each of these kinds

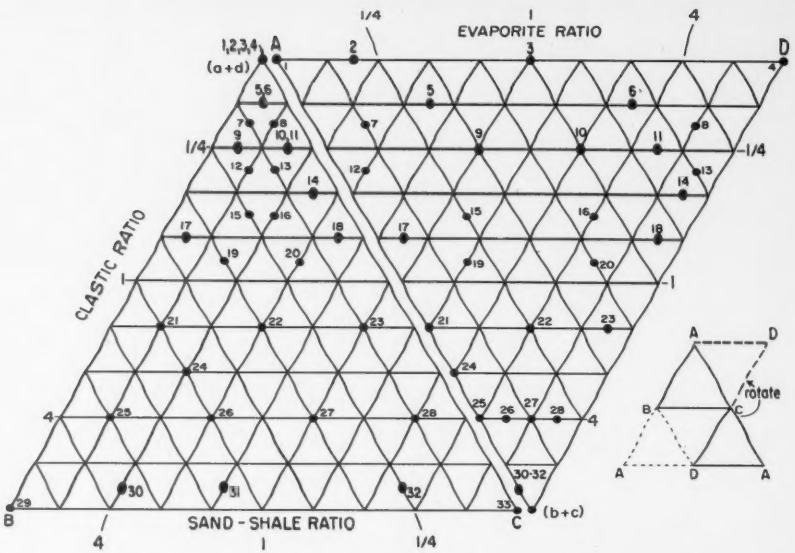

FIG. 7.—Two faces of tetrahedron showing points in table 2.
Inset shows relation of faces to developed tetrahedron.

of facies maps.

Table 2 lists 33 points selected to afford a reasonable distribution on and within an $ABCD$ tetrahedron, here representing limestone, sand, shale, and evaporite. The coordinates represent the percentages of the end members, and the last three columns list the clastic ratios, sand-shale ratios, and evaporite ratios of each point. Figure 7 shows the distribution of the points on the ABC and ACD faces. The ABC face shows the common clastic ratio and sand-shale ratio projection, with $a+d$ combined into the A end member, representing the non-clastics. The ACD face is the evaporite ratio triangle rotated as shown in the inset, with $b+c$ combined into the C end member, representing clastics. The clastic ratio scale is a series of horizontal lines common to the two faces. The sand-shale ratio, b/c, occurs on the ABC face, and the evaporite ratio, d/a, is shown on the ACD face.

The points in the system were distributed on a hypothetical map to show possible facies variations in an area where all four end members and a variety of end member mixtures occur. Figure 8 shows these data on conventional clastic ratio and evaporite ratio maps for comparison with later maps. In both instances the ratio limits were selected as $\frac{1}{4}$, 1, and 4, to simplify presentation.

It may be noted that the clastic ratio lines are common to both maps, and the differences arise from the secondary ratios used. The upper map of figure 8 shows the interplay of sand and shale in the southeastern part of the map, but combines carbonate and evaporite into a large northern area. The lower map, on the other hand, shows the interplay of carbonate and evaporite in the north and northwest, but does not show the relations between sand and shale. Each map serves its own purpose, however, and the two

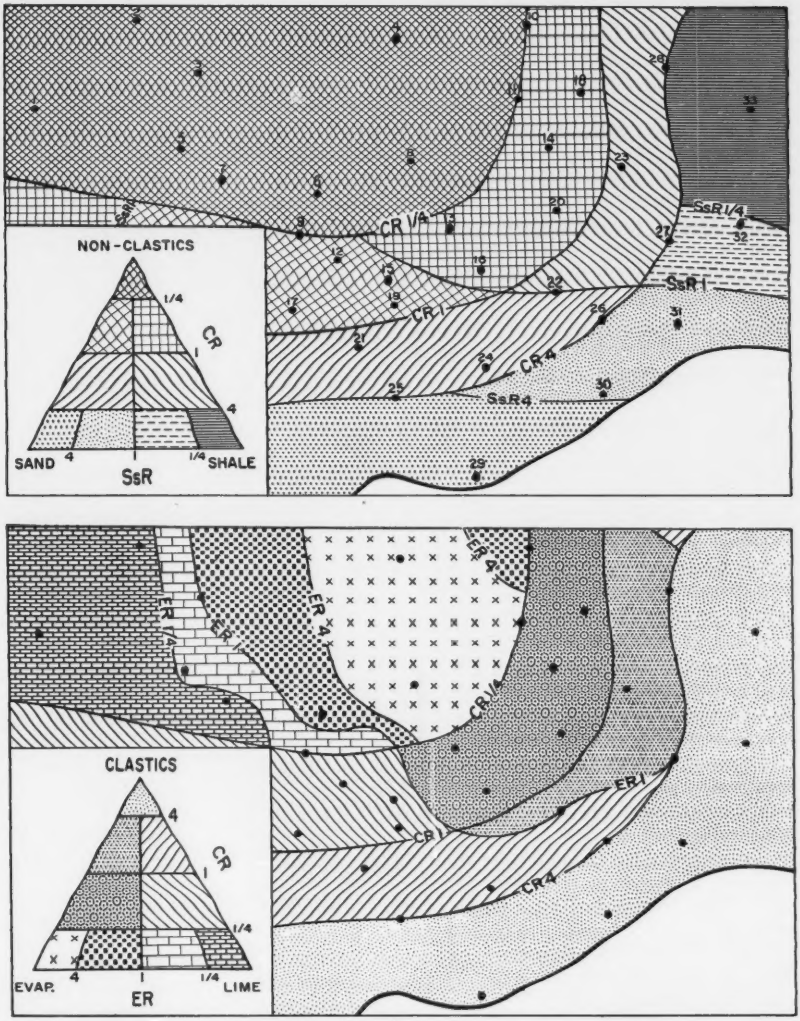

FIG. 8.—Facies maps based on figure 7 and table 2. Upper map shows conventional ratio triangle, lower map shows evaporite triangle.

maps bring out the importance of design in selecting end members or end member combinations to emphasize certain characteristics of the stratigraphic unit.

Figure 8 illustrates the *composite end member* method for showing four end

members. They are a form of "projection facies map" in that the interior points are brought to a selected face by projection along intersections of selected planes, here the clastic ratio plane and either the sand-shale ratio plane or the evaporite ratio plane. The *tetrahedral segment method*, which involves slicing the solid tetrahedron along selected planes, affords another kind of map. In this method the points within and on the tetrahedron are not disturbed, but are included in the tetrahedral segments produced by slicing.

Figure 9 shows two outline maps base on tetrahedral slices. The upper map is based on the tetrahedron sliced along clastic ratio, sand-shale ratio, and evaporite ratio values of $\frac{1}{4}$, 1, and 4. The lower map is the same tetrahedron sliced along clastic ratio and sand-shale ratio values of $\frac{1}{4}$, 1, and 4, and along evaporite percentage values of 20, 50, and 80. Comparison of these maps with those of Figure 8 shows that the pattern of clastic ratio and sand-shale ratio lines is the same as in the upper map of Figure 8, and that the evaporites have been superimposed as an overlay. The difference in overlay pattern in the upper map of figure 9 and the lower map of figure 8 arises from the cutoff of the $\frac{1}{4}$ and 4 evaporite ratio lines in figure 8, but not in figure 9. The latter therefore, gives a more complete picture of evaporite occurrence. There is no reason why the $\frac{1}{4}$ and 4 evaporite ratio lines in figure 8 should not be extended over the map, although usual practice is to limit them to end member segregation.

Figure 9 has been left in outline form because of the complex black-and-white patterns which would result from zipatone overlays. Such maps may be colored conveniently by using standard triangle colors, and indicating the evaporite areas by cross-ruling in ink directly on the color patterns. If separate colors are used for each tetrahedral segment, it will require 24 colors for the upper map of figure 9, and 18 colors for the lower map.

Four end member systems can also be mapped by slicing the tetrahedron along percentage planes. Figure 10 is a map based on the 50 and 80 per cent planes of the four end members of table 2. The pattern is relatively simple inasmuch as only nine tetrahedral segments are involved. The map shows segregation of the 80 per cent sand end member in the south, the shale end member in the east, the lime end member in the northwest, and the evaporite end member in the north central part of the map. The intervening areas represented by the central octahedron include all stratigraphic sections with less than 50 per cent of any end member.

The essential problem in mapping four end members by tetrahedral segments is one of simplifying the pattern to avoid undue complexity in pattern or color. In some instances it may be preferable to prepare separate maps of clastics and non-clastics, using simpler two and three component systems. There is, however, some advantage in having single maps for regional comparison. In any instance the decision to use the composite end member method or the tetrahedral segment method depends on the features to be emphasized. Different decisions may be called for in academic and economic applications.

The method of "facies projections," illustrated by clastic ratio maps, can also be applied to special studies not involving composite end members. One such is the use of trilinear projections on a selected face of the tetrahedron. In compiling the necessary data, one of the end members is omitted and the remaining three are recomputed to 100 per cent. If end member A is omitted, for example, the process may be visualized as a swarming of the interior points to face BCD along lines radiating from A, as illustrated in figure 2. In one sense this "filters out" the A component, and shows the relative interplay of b, c, and d on the BCD face.

Table 3 lists the trilinear coordinates of the 33 points in table 2. The evaporite (D) is omitted, and the recomputed percentages a', b', and c' are shown. Comparison of the two tables shows that

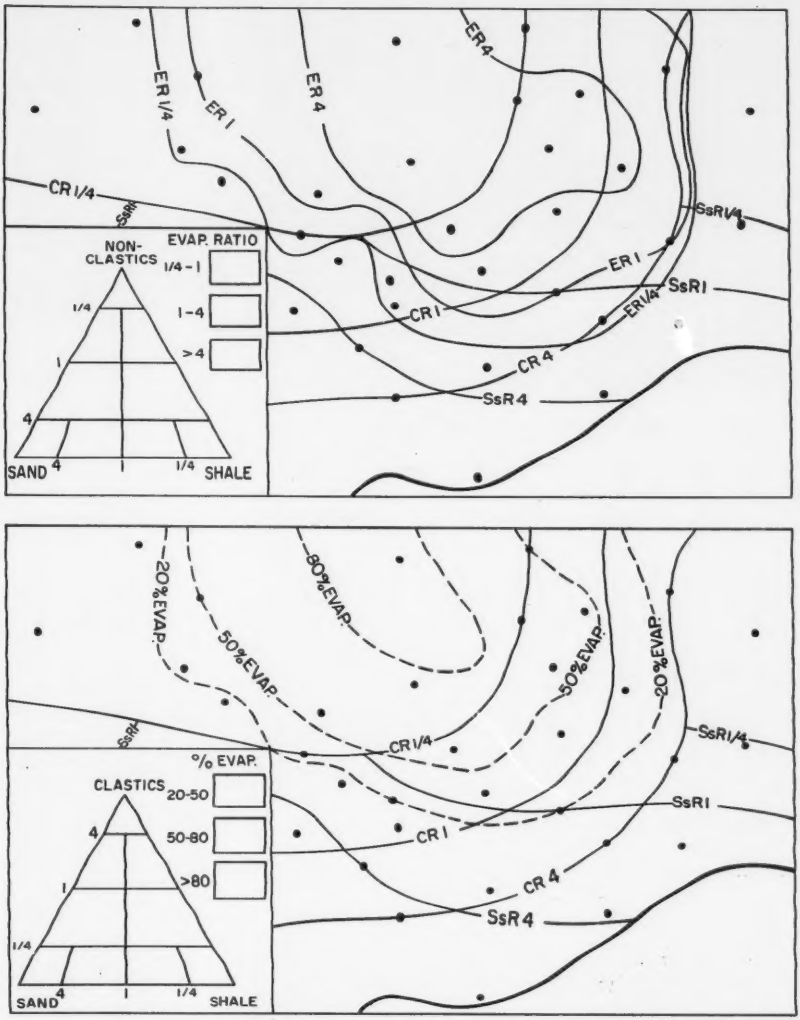

FIG. 9.—Facies maps based on figure 7 and table 2. Upper map shows conventional triangle with evaporite ratio overlay; lower map has evaporite percentage overlay.

whereas the percentage values of most points change during the transformation, the sand-shale ratios remain the same. This was brought out in connection with figure 3, which showed that the trilinear projection preserved the sand-shale ratio of the original interior point.

Preservation of the sand-shale ratio

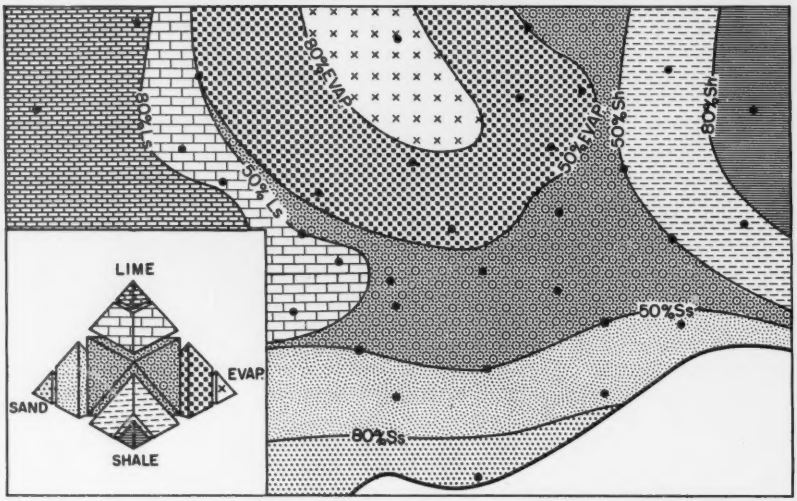

FIG. 10.—Facies map based on figure 7 and table 2. Tetrahedron sliced along percentage planes.

(or of the evaporite ratio if end member *C* is omitted) suggests that a trilinear projection facies map may be constructed by superimposing the trilinear limestone percentage on the original sand-shale ratio. For comparative purposes figure 11 shows two maps, the upper of which has the sand-shale ratio and the absolute limestone percentage. The lower map has the same ratio and the trilinear limestone percentage. The upper map shows the absolute relation between limestone and clastics, whereas the lower map translates this into a relative picture. The principal difference between the map patterns is the larger areal extent of the 20 and 50 per cent limestone areas in the trilinear percentage map.

The interpretation of trilinear projection facies maps is not always directly evident. In the present example, however, it may be seen that if the absolute limestone percentage is plotted against sand and shale, the impression gained (in part from the selection of contour values), is that the area of prevailing limestone is confined to the northwestern map area. The trilinear percentage shows that with respect to sand and shale the limestone actually forms a significant part of the section over the western two-thirds of the map area. In one sense the trilinear map shows the areal relation between influx of clastics and development of limestone without regard to the contribution of the restricted environment which produced the evaporites.

The writer has experimented with several kinds of projection facies maps, but admittedly work has not gone far enough to permit setting up criteria for circumstances under which these special maps are superior to tetrahedral segment maps or to the more common clastic ratio maps. The choice of 20, 50, and 80 per cent limestone lines in figure 11 was made to permit direct transformation to a (sand+shale)/(limestone) ratio, which is a form of the clastic ratio. In both maps the 80, 50, and 20 per cent limestone lines correspond to ratio values of $\frac{1}{4}$, 1, and 4 respectively.

Trilinear projections represent three end members for mapping, but the amount of fourth end member present influences the position of the projected point. Orthogonal projections are also affected by the values of the four components, and they present additional problems in designing facies maps. Orthogonals tend to cluster toward the center of the projection face as the amount of omitted end member increases, although points with no fourth component may also fall in the center of the triangle. Further study is needed to determine the most useful applications of orthogonal projections to facies maps.

As with two and three end member systems, four end member maps may be prepared for a variety of specific problems. Whether trilinear projections for such specialized maps have a discernible geological meaning depends somewhat upon the end members involved. Experimentation is implied. A further extension of ratios is also opened by four end members. Ratios of the type $(a+b+c)/d$ are possible, and provide points which plot along edges of the tetrahedron, thus giving rise to combinations of apparent two end members systems.

TABLE 3.—*Trilinear coordinates of points in table 2.*[1]

Point	Limestone (a')	Sandstone (b')	Shale (c')
1	100	0	0
2	100	0	0
3	100	0	0
4	—	—	—
5	77	7−	7−
6	72	14	14
7	83	11	6−
8	40	20	40
9	72	21	7
10	54	9	27
11	43	14	43
12	74	16−	10
13	17−	33	50
14	14	14	72
15	56	25	19
16	36	28−	36
17	58	37	5
18	11	11	78
19	47	35	18−
20	25	25	50
21	40	50	10
22	24+	38	38
23	8	15	77
24	30	50	20
25	20	70	10
26	16	53	31
27	11	33	56
28	6	12	82
29	0	100	0
30	5	75	20
31	5	55	40
32	5	20	75
33	0	0	100

[1] Values rounded off to whole numbers. Item (4) may be indeterminate. Such points cause complexities in trilinear mapping, not considered in figure 11.

CONCLUDING REMARKS

The common use of percentages and ratios in facies mapping indicates that only a limited part of the total framework of facies map design has been studied in detail. It was seen that any point within a tetrahedron can be projected as five points on each of four faces, and that the tetrahedron itself may be sliced in various ways. These geometrical properties open the way for considerable experimentation on additional ways of expressing facies relations. It may be that only a few of the total possibilities will be directly useful, but it seems equally likely that some new variations in technique based on other projections or on planes may permit more critical facies analysis than is now common.

The increasing usefulness of facies maps in a variety of academic and economic studies suggested this present attempt to establish a framework which could provide elements for rational design of facies maps. The present paper is in the nature of a progress report in this direction. Present standard types of facies maps can be designed for a wide range of problems, but occasionally one can discern features not explicitly brought out by such maps. It is possible that broader principles of design could make the implications more explicit. Tetrahedral slicing and projection facies maps provide

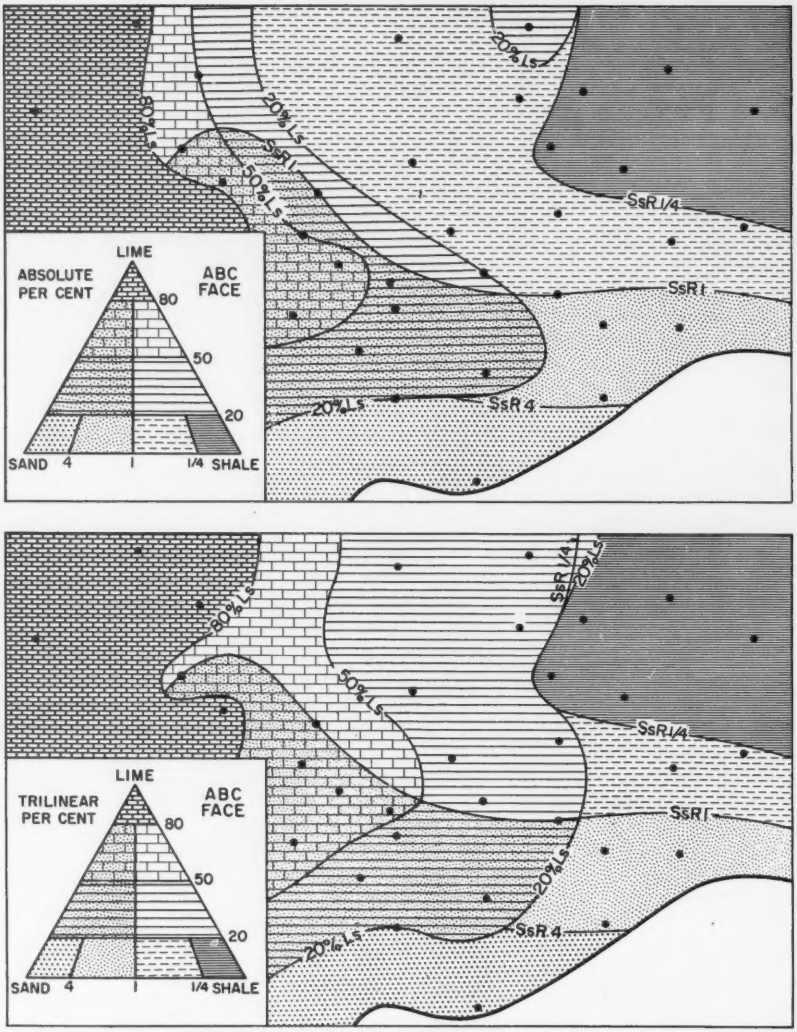

FIG. 11.—Facies maps based on figure 7. Upper map shows sand-shale ratio and absolute limestone percentage from table 2, lower map shows same ratio and trilinear limestone percentage from table 3.

some additional elements for such new designs.

It was emphasized earlier that the geometry of the tetrahedron lends itself to a wide variety of maps based on a large number of general or specific end member combinations. The question of the most appropriate technique for a given map is best answered by consideration of the end members involved and the objectives of the map. The writer's experience has been that the ratio approach for two or three end members commonly yields interpretable maps; and that for four end members some combination of three ratios, or two ratios and a percentage, provides a convenient method of mapping.

The problem of vertical variability maps, which show the arrangement or thicknesses of individual lithologies within stratigraphic sections, can be attacked in part by use of tetrahedral principles. However, this topic is not developed further here, owing to limitations of space and complexity of the subject.

The writer wishes to emphasize that although the present discussion is related to facies mapping, the geometry of the tetrahedron is independent of the uses to which it is put. Any system of two or more variables which totals 100 per cent can be used in the same framework. Where such variables are mappable, the basic geometry is the same as for facies mapping. Mertie's work (1948, 1949) in extending the use of tetrahedra to charting as many as seven variables on hypertetrahedral faces was related to plotting of chemical components, but its possible applications in facies work deserve detailed consideration.

The end member tetrahedron, used as a facies device, can also be considered as an isometric crystal, and the planes discussed in this paper could be described in terms of crystallographic axes. A collaborative manuscript on this aspect of the tetrahedron is in preparation.

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FIGS. 1–9, MARCH, 1954

PHOTOMICRO-STEREOGRAPHS AS AN AID IN INTERPRETING TEXTURES AND STRUCTURES

R. J. HUGHES, JR.
University of Mississippi, University, Mississippi

ABSTRACT

Photomicro-stereographs are advanced to show their usefulness in the interpretation of textures and structures. These stereograms were made with a binocular microscope and the practicability of the method is stressed.

INTRODUCTION

Stereophotogrammetry which gives an impression of location in space and three dimensional configuration is a useful, and relatively neglected technique in microscopy. It is difficult and at times almost impossible to properly interpret and compare textures or structures depicted on single photographs, and for this reason the value of photomicro-stereographs which can be examined with an ordinary stereoscope, recorded in publications, and filed for frequent reference cannot be overstated.

There are a number of devices on the market for taking stereoscopic photomicrographs. Such equipment is known under the trade names of Ortho-Stereo-Camera made by Bausch and Lomb Company, with similar equipment being made by Leitz, Inc., the American Optical Company, and others. These cameras are used with monocular microscopes, and are of proved excellence. However, since such equipment is beyond the means of the average worker, it is the purpose of this paper to describe a method by which stereoscopic photomicrographs can be made as easily with the binocular microscope. The accessory equipment in addition to a suitable camera can be quickly and inexpensively made in any machine shop.

The stereograms appearing in this article were made by the writer using the simple equipment described. They were selected for the illustration of the detail and clarity that is easily possible with this apparatus, using the two converging optical systems of the binocular microscope; and to present the effectiveness of three dimensional textural and structural study. Such stereograms serve as reference material and as a teaching aid.

PRINCIPLES OF STEREOVISION

In order to see stereoscopically, an object must be viewed from two positions parallel to it. Therefore a person who has only one eye cannot see stereoscopically, and to him the field of view always appears flat. Stereoscopic or binocular vision (stereopsis) is the result of superimposing two different views of an object into one composite picture by the power of coordination. The science of stereoscopy deals with the resultant three dimensional effect, and the methods by which it is produced. For the average person, the best distance for stereopsis is about ten inches from the eyes. At this distance the parallax angle between the images is approximately 15°, although the exact angle varies, depending on the interpupillary distance of each individual.

The angle between two views for full size objects should approximate 15°. Variations in the height of the object will be materially affected if the angle is greater than, or less than 15°. For an angle less than 15°, the height of the object will be lowered, and conversely,

for an angle greater than 15°, the height is accentuated.

Seeing stereoscopically is limited to a depth dependent on the small distance between the eyes, but stereogrammetry may use larger bases, requiring only an accurate base line, parallel to the object photographed.

To obtain a stereoscopic picture, two views must be taken from two positions parallel to the subject, and then the images mounted in correct alignment for stereo-viewing.

For small objects it is not necessary to move the camera if the object photographed is turned slightly for the two views.

EQUIPMENT

The equipment (fig. 1) used by the author for making his stereograms consists of an American Optical Company Stereoscopic Binocular Microscope, a Universal Microscope Illuminator with adjustable transformer made by the same company, an Argus C-III camera, a Speed-O-Copy unit with ground glass focusing, and a machined brass tube lined with felt to fit snugly over each eye piece tube of the microscope, one end of which is threaded so that it may be screwed into the lens plate of the Speed-O-Copy unit. Three small Allen head screws set at 120° apart prevent the camera from moving.

Exposure times were determined by a photometer Model 200, manufactured by the Photovolt Corporation of New York, although this piece of equipment is not essential for good photographs.

PROCEDURE

The two pictures comprising a photomicro-stereograph, as a rule cannot be taken at the same time, although if some specific problem warranted the expense involved in constructing special apparatus, it could be accomplished by utilizing one of the methods by which stereoscopic pictures can be produced. Living or moving matter necessitates taking simultaneous pictures, but since there is little need for pictures of living organisms in most geologic applications of stereoscopy, and since non-motile subjects can be photographed in two separate exposures, the latter procedure is entirely satisfactory.

FIG. 1.—Camera in position for photographing. Focusing unit has been folded out of position.

The procedure used by the writer is as follows:

(1) The specimen to be photographed is placed on the stage of the microscope to show the best detail.

(2) The specimen is illuminated to about the same degree of brightness as is comfortable for normal microscope work. For greater magnifications, the intensity of the light must be increased. A spot light of the type mentioned above should be used; the intensity being regulated by an adjustable transformer. This, of course, accentuates the shadows more so than would diffused light.

(3) The light intensity is then measured as the total light beam at the microscope exit. The search unit of the photometer is placed on an ocular adaptor

and a reading in foot candles is recorded, then converted to the correct exposure time by a nomograph or circular calculator provided for the purpose.

(4) After obtaining the exposure time, the search unit and adaptor are removed, and the Speed-O-Copy unit to which the camera is attached is installed. The Allen head screws are tightened to prevent movement of the camera (fig. 2).

(5) The Speed-O-Copy unit is made of three metal hinged plates (fig. 2), a camera plate with ring to which the camera is attached, a lens plate to which the camera lens is attached for macrophotography (brass tube is used in place of lens for microphotography), and a third plate to which is attached the ground glass holder for focusing. The focusing unit folds over to the position to be occupied by the camera (fig. 3), and the microscope is used for focusing. Inasmuch as the camera lens is not used, extreme care must be exercised to focus on as flat a surface as possible. There is no iris diaphragm in the microscope assembly, and for this reason it is impossible to stop down to obtain depth of field. Reducing the intensity of illumination increases somewhat the depth of field, but at the same time there is a decrease in clarity with loss of detail. Naturally, as magnification is increased, the depth of field becomes still more critical. So, for high power magnification (×144) the depth of field is practically nil.

FIG. 2.—Photograph showing camera, and hinge plate of Speed-O-Copy unit prior to focusing for picture.

FIG. 3.—Focusing unit in position.

(6) After properly focusing with the microscope, the ground glass unit is swung back to its original position and the camera swings down and is locked in place by a screw (fig. 1).

(7) The exposure is made by either turning on and off the light or operating the shutter if it is the focal plane type.

(8) The same procedure is repeated with the other tube of the microscope.

SUMMARY

The advantages of stereophotography are evident in the increasing number of stereophotographs employed in many fields of geology—as illustrations of aerial studies of terrain they are familiar, and are becoming more so in paleontology.

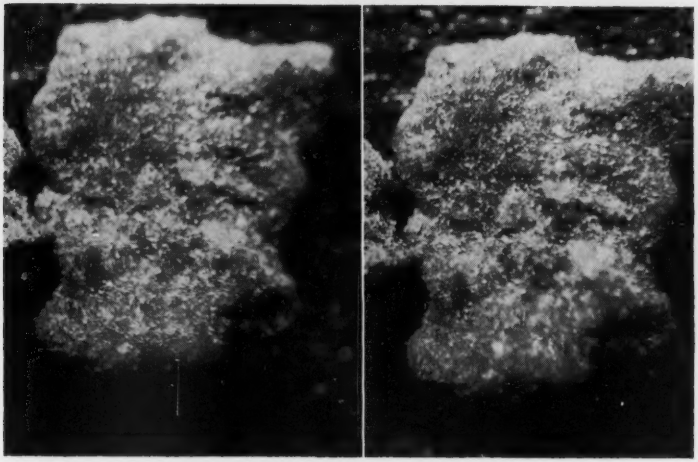

FIG. 4.—Medium-crystalline dolomite. ×36. Exposure time, 1 sec.

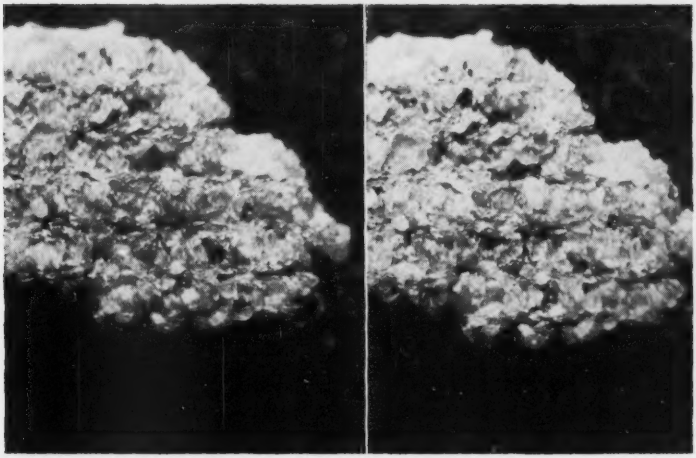

FIG. 5.—Ferruginous sand, fine to medium-grained, loosely cemented, with angular to subrounded grains. ×36. Exposure time, 1 sec.

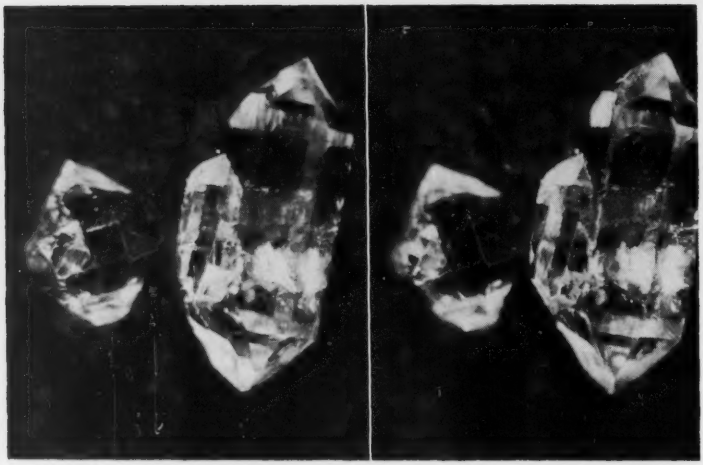

FIG. 6.—Doubly terminated quartz crystals. The two crystals are hexagonal bipyramids each. ×18. Exposure time, 1 sec.

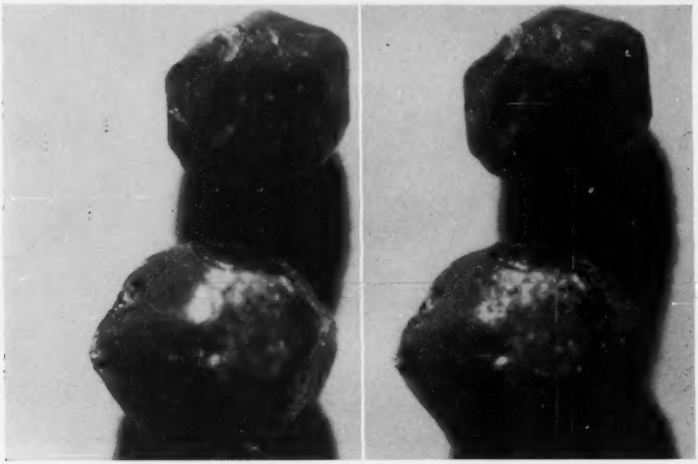

FIG. 7.—Typical garnet crystals exhibiting the dodecahedral habits. Note the chipped areas and the rounding of the crystal faces due to abrasion in transportation. Exposure time, 1/20 sec.

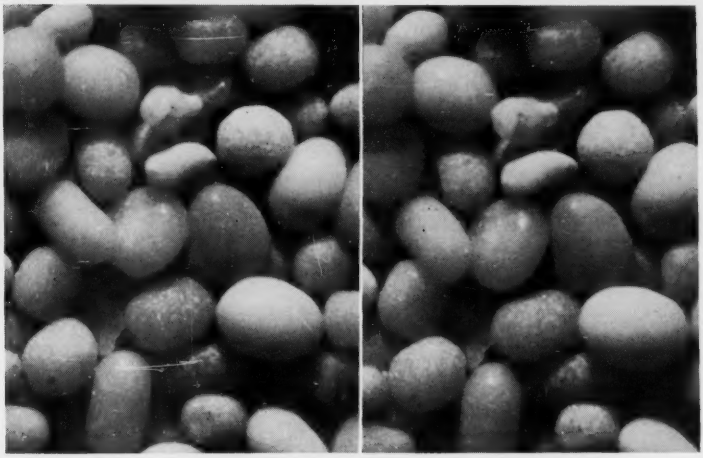

FIG. 8.—Ooliths. Note both cylindrical and spherical types with variation in surface texture, some being quite smooth, others pitted. ×54. Exposure time, ½ sec.

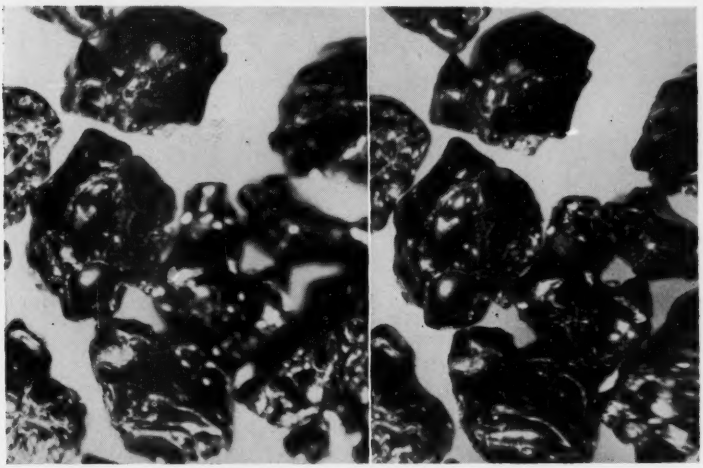

FIG. 9.—Black (obsidian) sand. Note the vesicular nature of the grains. ×18. Exposure time, ½ sec.

In microscopic sedimentology, spatial qualities are also of importance, and the technique of stereoscopic illustration is particularly well adapted to small items with prominent three dimensional qualities. Features of texture that are inconspicuous and might entirely escape notice, and structural details hidden in concavities where profile views cannot be obtained are frequently well displayed in microstereographs.

The perceptive usefulness of stereograms is generally intermediate between actual examination of samples and specimens, and the viewing of flat customary illustrations. In some cases, it is believed that the study of stereograms is better than the study of actual material. Certainly for teaching where microscopes are scarce and field trips expensive, stereograms are expedient.

The series of photomicro-stereograms accompanying this paper (figs. 4–9) show a variety of suitable textures and structures for three dimensional study. For comparison, examine the photographs first with a lens type stereoscope; then, one of the photographs of the stereo pair with the unaided eyes. Stereoscopic effects must be experienced to be fully appreciated.

For the petroleum geologist, stereoscopic aerial reconnaissance of geomorphic features has proved of inestimable value; stereoscopic micro studies should be of equal importance. Lack of widespread training in stereoscopic interpretation, encumbered with the usual expensiveness of the methods employed to produce and display stereoscopic illustrations, have delayed the technique of photomicro-stereography from receiving the development it deserves. The adaptability of the binocular microscope for making stereographs is simple, and the necessary equipment other than the camera, may be easily and inexpensively constructed. It should hasten the spread of photomicro-stereography.

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PLATES I–IV, TEXT FIG. 1, MARCH, 1954

STYLOLITE DEVELOPMENT POST-DATES ROCK INDURATION

H. V. DUNNINGTON
Iraq Petroleum Company, Ltd., Kirkuk, Iraq

ABSTRACT

Considered evidences show that stylolite formation succeeded rock induration in limestones of many ages from Middle East localities. Observations of B. M. Shaub, allegedly proving origin of some North American stylolites prior to consolidation, are examined and pronounced inconclusive as to relative times of stylolite formation and rock hardening.

Existing stylolite seams may facilitate subsurface fluid movement, thus affecting oil migration, accumulation and production. Stylolite development in limestones, like compaction in shales, causes expression of part of the contained fluids: *but such expression occurs late in rock-history, not predominantly at an early stage as in the case of normal compaction.* Stylolite formation entails local supersaturation of the solvent water, and consequent local redeposition, thus reproducing in many limestones the same type of fluid expression as is occasioned in some sandstones by cementation related to grain interpenetration.

INTRODUCTION

In a spirited and provocative paper, posing the question "do stylolites develop before or after the hardening of the enclosing rock?," B. M. Shaub (1949) dismisses as commonplace and insignificant the evidences brought by many authors to support the thesis of post-induration genesis in general, and the "solution-pressure" theory of origin in particular (for which see Stockdale, 1922, 1943, etc.). He reaffirms his faith in the "contraction-pressure" theory of stylolite development which was first formulated by him in an earlier contribution (Shaub, 1939), and he presents four photographic plates depicting stylolite features, with the confident claim that these provide evidence which is absolutely diagnostic in placing the time of origin of stylolites prior to the time of rock consolidation.

Surprisingly, no concerted response has been called forth from the defenders of the "solution-pressure" theory, though certain authors have rejected Shaub's account of stylolite genesis as inadequate to explain particular occurrences, for which they have demonstrated stylolite development after consolidation (Blake and Roy, 1949; Bastin, 1951), whilst many of the critical arguments of Stockdale (1943, etc.) remain uncontroverted by any of Shaub's several publications on the subject. Since the gage has been cast, however, and no champion has arisen to defy the challenger, it must now appear to the enquirer that the "Solution-pressurists" are vanquished, or at least abashed, by the strength of their solitary opponent. Yet the diagnoses of his own photographic evidence, detailed at length by Shaub, are manifestly ill-based.

The writer has concluded from independent observations that stylolites do not develop in calcareous rocks before consolidation; he also considers that stylolite formation has been of fundamental importance, in some areas, in causing and controlling oil migrations and accumulations in calcareous sediments. This paper is now proffered to discuss and dismiss the evidence of Shaub's later cited publication (thus removing one hindrance to general acceptance of the possible importance of the "delayed action" migration mechanism which is suggested herein), to present in brief some evidences indicative of post-induration stylolite formation, and to develop certain concepts which inhere in the adopted view that stylolites are secondary features of calcareous rocks.

DISCUSSION OF SHAUB'S "DIAGNOSTIC STRUCTURES IN STYLOLITE SEAMS"

The structures figured and diagnosed by Shaub (1949) are to be seen on polished faces of Tennessee marble in floors and walls of named public buildings in Ohio and Massachusetts. Discussion herein is based solely on the excellent photographs published by Shaub, no opportunity having arisen for the writer to view any of the wide-scattered Tennessee marble exhibits "*in situ*." One of Shaub's photographs (1949, fig. 3) is reproduced as plate I hereof; for detail of his other figures reference must be made to the original publication.

Keystone Offsets

In plate I part of a normal stylolite seam appears to be displaced from the main trace of the seam at H to a parallel position at G.

"The fault or slip planes along which the movement occurred are plainly shown. These planes together with the displaced section form a *keystone offset*" (Shaub, 1949, p. 31).

Shaub's remarks on such keystone structures are quoted (with abridgements and slight adjustments to render them apt to the available photograph) (pp. 31–32):

"A limited and restricted offset of this order could not occur in hardened rock unless the rock around it were badly broken. The length of section G is much greater than that of the gap in the seam from which it originated, thus showing that a considerable plastic displacement had occurred before the rock hardened." (Figure 1 bottom, Shaub, 1949, p. 32) " . . . shows another stylolite seam . . . where the displacements of the keystone wedges E–F and D–C are complementary. Again . . . the length of the displaced section is greater than the space from which it was displaced. Either the displaced sections were stretched or the gaps shortened by plastic adjustment. Hence these keystone sections or wedges present critical diagnostic evidence showing that the stylolite seams are not only earlier than the consolidation of the lime muds, but earlier than the formation of the displaced keystones, both operations occurring before the hardening of the rock."

It is only the disparity in length between gap and offset which confers upon the keystone features such significance as they are alleged to possess as indicators of the state of the limestone at the time of their development. Had the length of the gap been equal to or greater than that of the offset the structures would have aroused no comment, being then dismissable as normal major stylolite columns, themselves bearing a series of minor columns. Stockdale (1926, p. 409, fig. 6) illustrates such a major column, occurring on a seam which is otherwise characterized only by small columns, remarking that it illustrates a striking but common situation "testifying that the amount of rock removed by solution may be much greater than the length of the individual teeth of a stylolite might seem to indicate." Frequently encountered in material studied by the writer, but not in the literature, are step structures in stylolite seams, at which the seam abandons (for instance) one horizontal bedding plane for another, connection between the two planes being via a vertical plane which is usually scoured by vertical grooves and slickensided. A double step structure of this type, with the two steps reversed in sense, could produce in section the rectangular offset figured by Stockdale, without requiring more rock removal than is called for by the length of the longest minor columns.

The primary assumption in Shaub's account of the keystones is that the offset portions of the seams as seen in the only available plane sections were physically displaced precisely from the gaps in the main seams. There is no evidence that this was indeed the case, and there is suggestion in the photographic evidence proffered that it was not. Shaub does not make any mention of need for enquiry on this fundamental point and neglects the existence of a third spatial dimension in

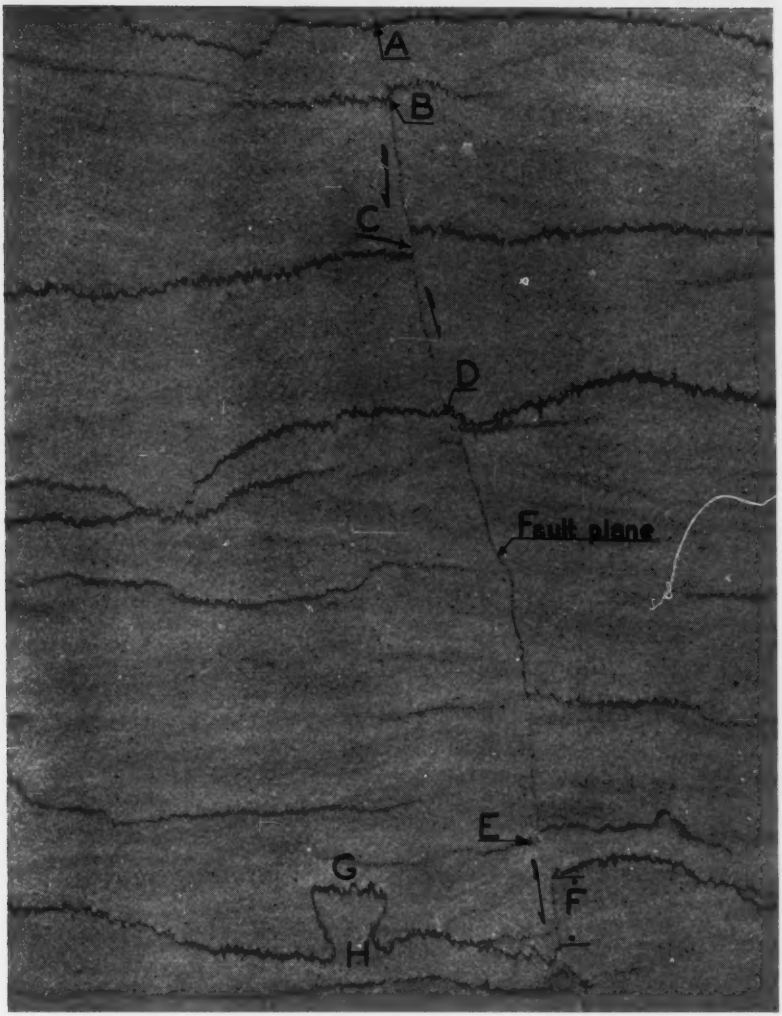

PLATE I.—Photograph of an area about 20×24 inches in a marble panelled wall of a room in the Hotel Cleveland, Cleveland, Ohio. The variable throws of the stylolite seams at the fault are explicable if the fault blocks moved relative to each other and perpendicularly to the plane of the section. The "keystone offset" at G–H can be interpreted as an oblique section through a normal stylolite column. Time of origin of the stylolites cannot be deduced with certainty from this evidence. (Photograph reproduced by kind permission of B. M. Shaub, and of the editor, from *Jour. Sedimentary Petrology*, vol. 19, no. 1, p. 34, fig. 3.)

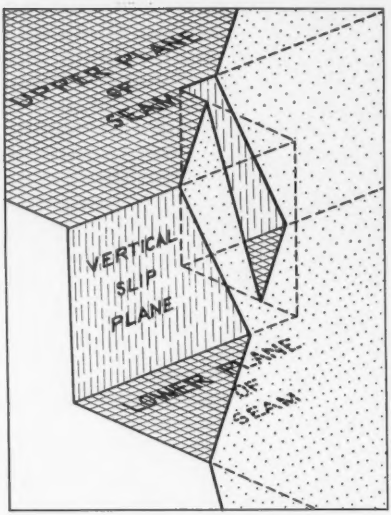

FIG 1.—"Complementary Keystone Offsets" produced on an oblique plane section by intersection with a stylolite seam having the form of a rectangular step structure. Stylolite columns are omitted. (Compare with photograph of "complementary keystone offsets" figured by B. M. Shaub, 1949, p. 32, fig. 1, bottom.)

his diagnoses of all the new evidence presented in his (1949) paper.

An alternative interpretation of the rather complicated case of the "complementary keystone offsets" is illustrated in figure 1. The form of the stylolite seam represented is that of a single step from one plane to a second parallel plane via three planes normal to the seam, two of which parallel each other and are normal to the third. The wedge shape of the offsets in the plane section is due simply to oblique intersection of the fundamental planes of the step structure.

If stylolites can develop in hard rock by rock removal to produce the results described by Stockdale and others, such a step structure as that illustrated can originate likewise after induration, and the fortuitously oriented ground surface from which Shaub illustrates his "complementary keystone offset" presents no useful or even novel evidence on which to base a preference for either pre- or post-induration origin.

It is not argued that the suggested explanation of the complementary offsets is necessarily the correct one, but merely that a credible account of the features is possible in terms of the "solution-pressure" mechanism advocated by Stockdale, without any need whatsoever to invoke plastic flow or readjustment. Credibility of the illustrated account is claimed. Accepting the solution-pressure mechanism for origin, it can be argued credibly that the stylolites of the seam and the slip planes of the step formed simultaneously and after induration of the rock, and that the offset was original and did not arise by actual physical displacement.

Yet another credible account may be devised for these offsets on the basis of obliquity of section through a major stylolite column of similar plan to that of the step in figure 1. Offsetting by physical displacement is here involved, but (accepting the "solution-pressure" mechanism of origin) offsetting is synonymous with the formation of the major column, and formation of small columns, slip planes and offset occurred simultaneously after hardening.

The evidence of the keystone offsets may thus be dismissed as non-diagnostic as to either mode of origin or time of origin of stylolites relative to induration.

Evidence appears in Shaub's figure of the complementary offsets to support the view that the keystone form is due to oblique sectioning of some such structure as that illustrated in figure 1: within the offset E–F there appears a small irregular *closed* stylolite or seam trace. This cannot be readily reconciled with Shaub's suggested mechanism of origin without admitting that the plane surface illustrated is oblique to the axis of the stylolite columns. This admission at once vitiates the argument that the offset portions of the seam originated by physical displacement from the gaps in the seam shown in

the plane of the section, which argument is fundamental to Shaub's interpretation.

Interlocking Loop Structures

Figure 2 of Shaub's 1949 paper (pp. 32–33) portrays "another type of stylolite seam displacement in the Tennessee marble . . . the seam is bent back onto itself, forming a kind of loop or roll. The serrations of the seam are continuous along the seam as it makes the loops at A and B. This structure shows that the *entire stylolite seam* has very "locally undergone a crumpling or folding during a period prior to the hardening of the rock; the formation of the stylolites is of course the product of a still earlier development."

Shaub's diagnosis of this illustrated evidence can be rejected. Along the course of the seam and on either side of it, are numerous *closed* traces of subcircular outline in the plane surface figured. These isolated closed traces find no mention in Shaub's account: they are obviously sections through and almost perpendicular to small stylolite columns which project upwards or downwards from a seam situated slightly above or below the plane of section in their vicinity. Clearly the plane surface photographed is ground sub-parallel with and intersecting a gently undulating seam which bears scattered small columns.

Random orientations of planes through normal stylolite features can produce sections showing interlocking seams, keystone offsets, keystone columns, columns with curved or irregular or sinusoidal walls, or with varied long axis orientation, and similar anomalous traces. The variability in plan-form and dimensions of columns, the variable presence and depth of longitudinal grooves, and the habitual irregularities of the seams permit a vast range of such anomalous traces, even if the departure from parallelism of column orientation and section plane is quite small. The solid form of such seemingly anomalous features must be verified before their significance can be weighed.

Differential Degrees of Faulting

Shaub attaches critical importance to the evidence shown in figure 3 of his paper (1949, p. 34), which reappears here as plate I. The essence of his argument is that the small fault, which runs from top to bottom of the illustration, cutting across several stylolite seams which are sub-horizontal, sub-parallel and gently undulating, produces small throws, varying markedly in magnitude, and even in sense, on the successive seams. He does not believe:

> "... that such pronounced differential displacements of the size illustrated could possibly occur in such limited space in a hard brittle rock without the adjoining material showing abundant evidence of dynamic disturbances. There are no such disturbances present. Hence we are brought to the conclusion that the faulting and development of the differential displacements as shown and the keystone offset were produced in unconsolidated plastic sediments, and since the stylolite seams are earlier than the displacements they too were developed at a time when the sediments were plastic" (1949, pp. 33–34).

Beneath the original figure Shaub enquires:

> "How could displacements of the order of magnitude shown be obtained in other than highly plastic material?"

Again there is a self-evident response. Displacements of the nature and magnitude shown are *inevitable* if the stylolite seams depart appreciably from parallelism, and if the fault had a horizontal component of movement, *in the sub-vertical plane normal to the figured section:* it is legitimate to suppose that the fault movement had such a component unless it is demonstrable that it had not. Hence the circumstances shown in plate I can be ascribed credibly to origin after rock hardening. The evidence is therefore not diagnostic as to relative times of faulting, stylolite origin, and rock induration. Shaub's account, or the alternatives of post-induration stylolite formation and

faulting, or of pre-induration stylolite formation and post-induration faulting remain arguable.

The displacement F on the seam carrying the keystone structure G–H is larger than any other seam displacement, and approximately of the magnitude required by the postulate that a step-structure, oblique sectioning of which produces the keystone trace, lies just behind (or in front of) the surface figured, and is cast forward (or backward) into the plane of the section by relative horizontal movement of the two fault blocks.

If the keystones are due to oblique sectioning of square-edged step structures which are related directionally to an early rectangular joint pattern, polished surfaces showing occasional keystone offsets should also show occasional V-sided offsets corresponding to intersections with downsteps. Suggestions of two such offests appear in the left hand fault block of plate I, one on the topmost seam to left to the displacement A, and another on the seam which carries the displacement D: the last noted is (significantly) a "split" seam.

Adhesion Ridges

In an earlier publication Shaub (1939) figured (fig. 6, p. 59) and briefly described (p. 58; p. 60) as "adhesion ridges" some transverse features noted on part of the walls adjoining a stylolite column in a specimen of Lockport dolomite from the dumps along the south bank of the Erie canal at Lockport, N. Y. The usual vertical striations of the column socket are

> " . . . crossed by transverse ridges believed to be caused by adhesion between the column and the wall during continued volume contraction after the column had pierced the adjoining plastic material" (caption to fig. 6, Shaub, 1949).

These features are "common on a number of columns from this locality" (Shaub, 1949, p. 60), but do not appear to be noted from elsewhere. No comparable features have been seen during examination of very numerous individual columns of many ages from Middle East localities.

To support his interpretation of origin of the "adhesion ridges," Shaub illustrated that similar ridges can be raised in wet plastic clay by impressing a block of wood and then "breaking contact" (Shaub, 1949, figure 8, p. 59). This alchemical demonstration must serve instead of detailed description, for we are left uninformed as to the amplitude of the ridges, the degree of correspondence between the positions of ridges on corresponding columns and socket walls, the width of the gap between wall and column, and the nature of the material (if any) filling this annulus.

From the published description and illustration it seems reasonable to argue that the ridges are subsequent and probably quite recent features, analogous to the minute horizontal fluting produced on vertical or near-vertical walls of many limestone caverns by solution activity of descending films of water. Location above the present permanent water table lends support to this suggestion, which is alternative to and as credible as Shaub's interpretation.

Pending firm demonstration that the transverse ridges of the Lockport columns and walls correspond entirely with expectations assuming adhesion during contraction, and that no alternative explanation compatible with origin after induration can be supported, the "adhesion ridges" cannot be used as evidence of pre-induration origin even of the Lockport stylolites. These rare, ill-described, and ambiguous features do not aid at present in determining the time of development of these stylolites relative to that of rock hardening.

Additional "Critical Structures" (Shaub, 1939, 1949)

Several other described and figured structures from Shaub's papers, to which he attributes some importance in furnishing demonstration of plasticity at the

time of stylolite origin, have been adequately discussed by Stockdale (1943) or (in anticipation) by Stockdale (1922, 1936), Bastin (1933, 1940) and others. The theoretical objections raised by Shaub in 1939 against the "solution-pressure" hypothesis of Stockdale have found some response in the latter's latest general contribution to the subject (1943), though Shaub retains till now the last word in this controversy. Most of the evidence brought by him hangs on rare or unique specimens not available to the writer, of which discussion is unjustifiable and unnecessary.

Shaub claims commendably that:

"Any amount of commonplace evidence offered in support of any theory might be invalidated by a single bit of critical, diagnostic evidence which has been overlooked, or not correctly evaluated."

The foregoing account deals harshly with the four types of evidence which Shaub regards as "pertinent, critical, diagnostic criteria not involving unknown or doubtful phenomena," and demonstrates that each can be construed reasonably without abandonment of the thesis that all stylolites develop after induration of the rock. It does not of course follow that this thesis is correct.

"SUBAQUEOUS SOLUTION THEORY"

Prokopovich (1952), raising the same objections to "solution-pressure" origin as does Shaub, proposes a theory which admits removal of material by solution but argues that solution precedes consolidation.

He contends that solution occurs at the sediment-sea water interface owing to and controlled by variations in water character. Stylolites he deems analogous with lapies on exposed limestone surfaces, whilst striated walls are compared with the grooved walls produced by rain water run-off on capped earth pillars in the subaerial realm. Cutting of fossils in column walls is unsatisfactorily explained, whilst cutting of fossils in socket walls is neither mentioned nor explicable.

The analogies are very strained, and found features of described stylolite occurrences do not correspond with anticipations which would follow from adoption of the theory.

Stylolites, if analogous with lapies, should have very variable form, only rarely including vertical columnar elements: in actual seams the columnar habit is ubiquitous. Curved, distorted and "keystoned" columns should be common if the seams developed in very plastic material: in fact such oddities are conspicuously rare. Longitudinal striations, if developed as are vertical channels on earth pillars (some unstipulated problematical agency replacing rain-water run-off), should appear on sloping as well as on vertical column surfaces, and should be absent from downward projecting columns (presumably to be explained as solution pit fillings in this account): in actuality, striation is ubiquitous on vertical column walls, but absent from sloping faces. If developed at the sediment-water interface and terminated by renewed sedimentation, overlying sediments should be normal, contained fossils should be entire, and occasionally impressed into column walls, each stylolite seam should represent an erosional unconformity, so that top-and-bottom relations should be apparent, at least locally; the overlying sediments should sag into the precedent hollows and drape over the protruding column ends. In actuality, cutting relations are identical above and below a seam, fossils are never impressed into column walls, and sagging and draping of the upper sediments is not found. If formed at the sediment surface in seas inhabited by benthonic organisms, columns should show frequent modifications appropriate to organic activity: such modifications are not found. Prokopovich cites fucoids on a seam as evidence of contemporaneity of stylolite development and life activity, but if the fucoids are insoluble, occur-

rence on a horizontal seam is compatible with a "solution-pressure" origin. He also records a single belemnite penetrating a vertical seam: no details are given so that this evidence is indecisive.

The main thesis of Prokopovich does not offer a credible account of normal stylolite features: it is a partial reversion towards the long-abandoned erosion interpretation of Quenstedt (1853 in Stockdale, 1922, p. 23). Wagner (1913), drawing evidence from the same formations as were studied by Prokopovich, concluded that the seams had formed by solution of hard rock.

Prokopovich cites vertical seams in a formation lying between rocks containing only horizontal seams, and denies any relationship of column orientation to the tectonic framework: the "solution-pressure" theory requires that column orientation should relate to pressures effective at the time of development; the tectonic element need bear no relation to later or earlier obviously manifested earth movements, and very embracing examination of tectonic and depositional history would be necessary before denial of directional control of interpenetration by tectonic pressure could be confidently advanced or accepted. Wagner (1913) found evidence of tectonic control of interpenetration directions in the formations in which such control is denied by Prokopovich.

Prokopovich suggests that vertical seams may be due to solution in soft sediments below the sea floor. This suggestion, rather than the very vulnerable main thesis, may father a theory of origin which could be a formidable alternative to the "solution-pressure theory," if only because disproof would be difficult. It may appeal to those who see insuperable difficulties in accounting for curved stylolites, curved striations, and other anomalous features by any hard-rock solution mechanism. Such a theory would account for cutting relationships with fossils and other hard soluble objects, but not for relationships with faults, unconformities, and some other features remarked on by Stockdale (1943, etc.). Compromise might be reached by recognition of two processes of origin, involving rock removal by solution, respectively of indurated and of consolidated calcareous material.

The evidence cited by Prokopovich does not prohibit belief in hard-rock origin for the stylolites described by him, and origin of any class of stylolite prior to induration remains to be firmly demonstrated.

EVIDENCE OF AGE OF STYLOLITE DEVELOPMENT FROM MIDDLE EAST SECTIONS

In recent years the writer has had cause to examine a very large number of limestone rock samples (field samples, well cores and cuttings) from many surface and subsurface localities in the Middle East, limestones of every age from Carboniferous to Miocene being represented. Examination, based primarily upon randomly oriented thin sections, since the rocks are generally too indurated to yield satisfactory separated solid microfossils, has been primarily for the purpose of paleontological age determinations, to which observations of such lithologic features as stylolites have been incidental.

Active interest in stylolites was first aroused by the finding that in the Ain Zalah limestone oilfield in Northern Iraq, which produces oil from fractures in an otherwise unpermeated globigerinal limestone, some microstylolites carry oil, and seemingly abet the open fracture system in maintaining subsurface fluid connection through the field. Dating of the ages, or relative ages, of stylolite formation and fracturing might thus be useful in dating the time and elucidating the manner of oil accumulation; as a background to such dating, enquiry into time of incidence of stylolites in other fields and areas became desirable.

Because of current disharmony between the majority viewpoint, voiced

by Stockdale (1922, 1943, etc.), that stylolite formation succeeds rock consolidation and occurs by solution under the influence and directional control of pressures in the rock column, and the dissenting claim of Shaub (1939, 1949, etc.) that stylolites are pre-induration features resulting from plastic readjustments without rock removal by solution, criteria were established by appeal to which time of origin relative to time of rock induration could be established on a consistent basis for any number of specific occurrences. The definition of stylolites was regarded as sufficiently vague to accommodate superficially similar structures arising in either plastic or indurated rock.

Prokopovich's (1952) "subaqueous solution" theory was published after completion of this work.

With reservations noted below the following relationships were taken as indicative of stylolite origin after rock induration:

Stylolites cutting initially indurated elements, specifically:

ooliths, fossils, pebbles.

Stylolites cutting elements reckoned crystalline from time of origin:

crystalline infillings of hollow fossils.

Stylolites subsequent to secondary phenomena to which hardening is prerequisite:

fracturing, brecciation, veination

coarse grade recrystallization, dolomitization, marmorization.

Many other possible relationships come to mind, but it was assumed that useful application of findings would be limited to interpretation of small unorientable rotary well cuttings. Consequently macroscopic relationships with large-scale rock features (bedding, unconformities, faults, etc.) were not expected to fall within notice. (In practice, with due allowance for obliquity of section, the spatial relationship of seams and columns to depositional bedding indicated by color or lithological lamination, long axis orientation of fossil elements, compressed microfossils and ooliths, etc., has very often proved readily feasible in thin sections of small rotary cuttings.)

Shaub (1939, p. 55) has argued that penetration of fossils by stylolites may be apparent but unreal, the frequent association of columns with holes in, or extremities of, fossils or fossil fragments being merely fortuitous. Alternatively, according to Shaub, "when the shells are of paper thinness and possess relatively low resistence to shearing," stylolite columns forming in soft sediments may cut such shells, carrying fragments forward in the moving column.

Neither of these accounts can satisfactorily explain the oft-encountered type of situation exemplified by Stockdale's figure of stylolite columns piercing deeply into a massive stromatoporoid (Stockdale, 1943, fig. 2, p. 10). Sheared fragments are clearly absent from the columns here, whilst it is an insupportable strain on credulity to suppose that neatly parallel columnar cavities, equipped with vertical striae closely simulating the striations of stylolite sockets, originated in the stromatoporoid before deposition (but after growth), and that the fossil then became aligned fortuitously not only in the direct course of a future stylolite seam, but with its cavities directed parallel to the columns of this future seam, of which a few were destined to coincide precisely in position with the pre-arranged sockets.

Yet, in deference to Shaub's objections, it is admitted that apparent cutting relationships between stylolites and single or occasional fossils (or ooliths, or pebbles) may be unreal or misleading, and not necessarily indicative of stylolite origin in hard rock. Such associations should be disregarded in assessment of time of stylolite development: but where fossils (or ooliths, or pebbles) associated with stylolites are cut, whilst those not so associated are entire, or where the proportion of stylolitized cut to unstylo-

litized entire fossils (or ooliths, or pebbles) is unduly high, stylolite origin after induration is indicated. Also where the intersection of seam with fossil or other initially indurated element is very complex, with multiple columns cutting through or into the latter, post-consolidation origin is to be accepted.

Development of microstylolitic interpenetration at points of contact of ooliths (Bastin, 1940, p. 214) and pebbles (Stockdale, 1922, p. 16; 1936, p. 133), well known and well reported in the literature, demonstrates microstylolite formation subsequent to induration of these elements only, but is uninformative as to the state of the containing rock at the time of development. Mutually impressed fossils with sutural or microstylolitic contacts are a precisely parallel case, equally uninformative as to the state of the rock at the time of interpenetration of the hard fossil fragments. But where a stylolite seam passes indiscriminately from matrix to oolith (Bastin, 1951), or pebble, or fossil, through the rock mass, or where stylolites at interpenetrating contacts continue through the rock matrix, a near-uniform physical state for matrix and ooliths (etc.) may be justifiably assumed, and since the ooliths, or pebbles, or fossils are indurated from the time of deposition, post-induration stylolite development is indicated.

"Hollow" fossils, infilled with clear crystalline calcite (or more rarely dolomite) are only anticipable in muddy fine grained limestones if the apertures to the environment are of sufficiently small dimensions or complicated form to exclude finely suspended muds. Stylolite seams frequently cut such fossils, the relationship being striking in thin sections of argillaceous globigerinal limestones. If the excised portion of test is of large size, it is apparent (though not inevitably true) that the development of the seam must have caused the excision, otherwise the fossil interior would have been filled with matrix mud. This argument provides a weak basis for acceptance of post-induration origin, which is strengthened immensely if several such stylolite-crystal mould relationships are found on one seam, and/or if comparable fossils with small natural holes unconnected with stylolites are found to be mud-filled.

Stylolites cutting matrix and pebbles of a conglomerate can only be regarded as demonstrative of post-induration age if induration of the pebble at the time of stylolite formation is assured. Soft rock conglomerates are probably more common in the geological record than in the literature. A positive demonstration of pre-stylolite pebble induration is claimed if substantial age difference can be proved between pebbles and matrix, or between two affected pebbles: failing such proof, enquiry into the nature and stratigraphical significance of the conglomerate often yields suggestion as to initial state of the pebble components to enable a tentative dating of stylolites relative to matrix hardening.

Stockdale (1943, p. 6) asserts that metamorphism of limestone to marble would erase pre-marmorization stylolite structures, and that well defined stylolites in such rock must post-date the metamorphic processes involved. The degree of erasure would clearly depend on the degree of metamorphism and the thickness of the stylolite seam. Accepting Stockdale's view that the seam consists of insoluble residue of dissolved limestone it appears that low grade metamorphism would not necessarily obliterate or even obscure a thick seam, though thinner seams would probably suffer loss of definition or erasure. Evaluation of the times of stylolite development and of marmorization (or recrystallization or dolomitization, etc.) in any specific case must depend on evaluation of the original deduced seam characters and of the degree of obliteration of other rock structures. Decisive demonstration of post-marmorization development of

seams will often be impossible, but hair-thin seams of clear definition, too tenuous to have served as barriers to fluid movement, in coarse grained recrystallized limestones from which original sedimentary structures have been erased, give grounds for powerful presumption of such origin. In thin sections, termination of crystals at irregular faces against the seam may demonstrate post-recrystallization stylolite development in some cases.

Fracture Evidence

Though Stockdale calls attention to stylolites developed along major unconformities (1943, p. 6, etc.) and along joints and faults, there appears to be no mention in recent literature of the relationships existing between stylolites and fractures directed *across* them.

It may be taken that with obvious but rarely encountered exceptions, fracturing and true brecciation only occur in indurated rocks. Open fractures and breccias are unlikely to yield useful evidence of relationship to stylolites, at least in samples recovered from wells, but mineralization of fractures by calcite deposition often preserves a permanent record of past hard-rock displacements to which stylolite structures may be relatable. In such material the abrupt termination of a calcite vein at a stylolite seam, particularly if fortified by a continuation of the vein laterally displaced along the seam, provides a fairly firm demonstration of post-mineralization, post-fracturing, post-induration stylolitization. Often a complex system of calcite veining may be discerned, and fairly precise spatial orientation of veins, rock displacements, stylolite seams and columns, and depositional bedding can be obtained from small rock cuttings studied in thin section.

Where all represented calcite-filled fractures cut and displace stylolite features, stylolite development prior to the earliest phase of fracturing must be admitted, and if other evidence of time of origin is lacking, possibility of origin during the early stages of consolidation may be admitted.

Criteria for Pre-induration Origin

If stylolites have formed in soft sediments, somewhat as suggested by Shaub (1939, 1949), proof of such early origin will be more difficult than is that of origin after hardening, since the time available for operation of pre-induration index processes on which dating of origin must depend will have been much briefer than has the post-induration period, whilst many post-induration processes tend to obliterate the evidence of early events.

Apart from early diagenetic processes (themselves usually difficult to relate to a time of operation relative to rock induration) only soft-rock deformation phenomena and modification of structures by contemporaneous organic activity appear to hold promise as possible reference features.

Slump brecciation and folding are often met in Mesozoic rocks of north Iraq: such associated stylolites as have been observed have usually been shown to have originated after the operation of the soft-rock process, and often after intensive fracturing for which late Tertiary age is here probable. Careful studies in the field would be necessary before it could be asserted that none of the observed stylolites was of soft-rock origin.

No modifications of structures by organisms have been seen in the material studied.

If stylolites have formed by solution in soft sediments before lithification, after the fashion loosely suggested by Prokopovich (1952), evidences of rock-removal by solution are not sufficient for determination of time of origin relative to induration. Proof of such mode of origin will require evidence similar to that required to support Shaub's "contraction-pressure" theory, and will be similarly elusive, but denial of such

origin will usually be more difficult than is denial of Shaub's explanation; only subsequence to secondary phenomena to which hardening is prerequisite can afford positive proof that soft-rock solution has not been the formative mode.

Summary of Findings

The accompanying photographs (pl. II to IV) typify commonly encountered situations which enable firm or qualified determination that the origin of stylolites occurred after rock hardening. No full record has been kept of the occurrence of different types of stylolite relationships in the large number of samples coming under notice: conclusions derived are based on cumulative personal impressions. As a limited project, thin section collections of rock sequences of various ages, selected at random from the much larger serial collections available, have been examined, the criteria as qualified above being rigorously applied. The results of this examination are summarized in table I. Study of macroscopic stylolites in the field, in field samples and in well cores has provided abetting evidence, and additional evidences of different types not herein considered, but in harmony with the conclusions based on the much larger number of microscopically studied samples.

TABLE I.—*Relationships between stylolite seams and other rock features in representative rock suites from North Iraq localities. (A single stylolite seam might cut fossils, pebbles, ooliths and vein sealed fractures: such a seam would be recorded once under each heading, once only in the total (A), once in the total (B), and once in the total (C) columns).*

Age of Rock Sample Suite	Number of		Number of Seams Showing Rock Removal										Number of Seams Showing No Diagnostic Feature
			I. Time Unknown: Stylolites Cutting					II. After Induration: Stylolites Cutting					
	Thin Sections Used	Seams Noted	Fossils	Fossil Moulds	Ooliths	Pebbles	Total (A)	Filled Fractures	Sealed Breccias	Crystalline Rocks	Total (B)	Total (C)	
1. Miocene	335	30	10	6	6	6	11	6	1	—	6	12	18
2. Oligocene	[1]615	82	45	6	—	—	50	11	—	12	20	63	19
3. Eocene	420	693	432	164	7	—	474	62	3	45	101	495	198
4. Paleocene	420	3,692	2,877	291	—	27	2,891	137	25	—	143	2,920	772
5. Cretaceous (U)	600	2,980	1,230	920	—	—	1,432	1,860	210	—	1,902	2,472	508
6. Cretaceous (M)	450	993	472	68	3	5	483	199	102	149	322	792	201
7. Cretaceous (L)	500	1,398	422	73	29	107	543	922	17	15	927	1,344	54
8. Jurassic (U)	500	820	213	35	425	29	517	91	27	211	234	682	138
9. Jurassic (M)	500	1,790	635	32	379	47	892	411	295	17	510	1,199	591
10. Jurassic (L)	600	942	125	47	472	—	525	287	181	67	327	719	223
11. Rhaetic	70	139	6	2	64	—	65	29	13	32	43	103	36
12. Triassic	855	1,320	569	230	489	—	897	192	130	311	392	1,098	222
13. Permian	417	555	340	81	25	8	348	68	17	117	183	428	127
14. Carboniferous	117	135	78	48	24	3	78	54	2	9	57	99	36
Totals	6,399	15,569	7,454	2,003	1,923	232	9,206	4,319	1,023	985	5,167	12,426	3,143
Percentage of Total Seams Noted Showing Relations Indicated			(a) 47.9	(b) 13.9	(c) 12.4	(d) 1.5	(e) 59.1	(f) 27.7	(g) 6.6	(h) 6.3	(i) 33.2	(j) 79.8	(k) 20.2

Percentage of Total Seams Noted Showing Relationships Compatible with Origin by:
i) compaction pressure mechanism before rock induration (Shaub, 1939, 1949) (k only) 20.2%
ii) solution pressure mechanism before rock induration (Prokopovich, 1952) (k+e only) 79.3%
iii) solution pressure mechanism after rock induration (Stockdale, 1922, etc.) (All) 100 %

Localities

1. Euphrates limestone, Qarah Chauq Dagh.
2. I.P.C. Kirkuk Well, No. 109.
3. M.P.C. Butmah Well, No. 1
4. Sinjar limestone, Ghilazarda.
5. M.P.C. Ain Zalah Wells, Nos. 19 and 16.
6. I.P.C. Kirkuk Well No. 109.
7. Qamchuqa limestone, Surdash, Kurdistan.
8. M.P.C. Najmah Well, No. 29.
9. M.P.C. Adaiyah Well, No. 1.
10. M.P.C. Butmah Well, No. 2.
11. Baluti shale, Sarki, Amadia.
12. M.P.C. Qalian Well, No. 1.
13. Chia Ziari formation, Ora, Kurdistan.
14. Harur limestone, Kaista, Kurdistan.

[1] Exceptionally small area of rock slice per thin section.

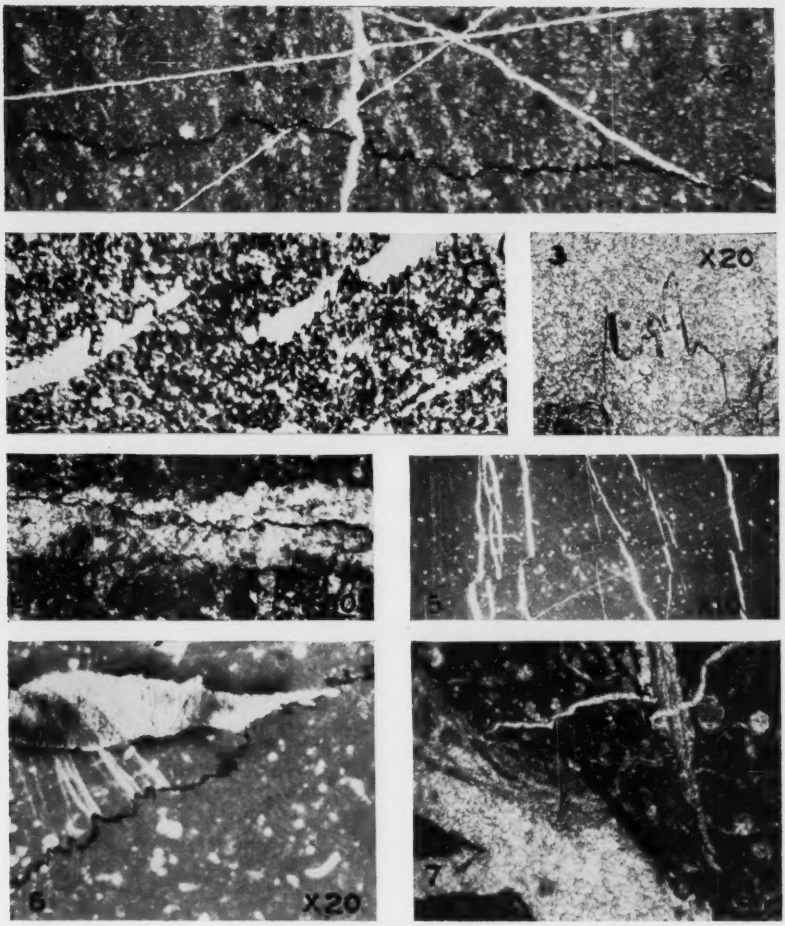

PLATE II. Relations of stylolites to calcite-filled fractures, and to diagenesis.

FIGS. 1 and 5.—Calcite veins displaced along stylolite seams due to rock removal.

FIG. 2.—Stylolite columns penetrating into crystalline calcite which fills a tectonic fracture. Where crossed by the seam the vein is displaced by more than the length of the longest column.

FIG. 3.—Columnar microstylolite in limestone from which original texture has been erased by recrystallization. The column walls are only about 1/200th millimeter thick, but are clear-cut and undistorted. The seam probably succeeded recrystallization.

FIG. 4.—Calcite vein bounded by stylolites, and entirely containing a central seam.

FIG. 6.—Stylolite—terminated displacement vein, with subordinate veinlets.

FIG. 7.—Two-generation vein complex, with termination of (wide) veins at stylolites, and displacement of later (narrow) vein at each seam surface.

Stylolites illustrated in Figs. 1, 2, 4, 5, 6 and 7 originated after calcite deposition had sealed fractures which formed in hard rock. All veins illustrated infill mechanical fractures without modification of fracture walls.

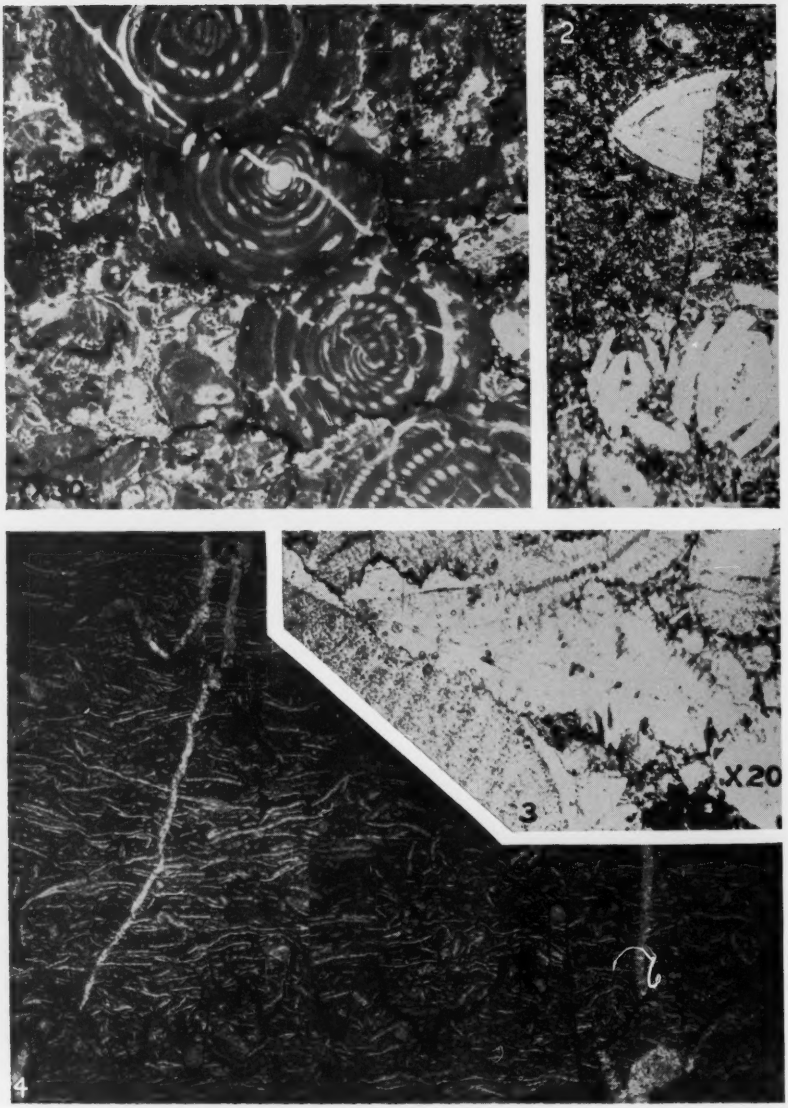

PLATE III. Some stylolite-fossil relationships.

FIG. 1.—Interpenetration of alveolinids along seams which pass out into the limestone matrix. Note calcite vein displaced at upper seam and terminated at central seam. Stylolites developed in hard rock after fracturing and calcite sealing.

In no single case has it been demonstrable that a stylolite originated prior to rock hardening, whilst a very high proportion of seams observed can be shown to post-date induration, usually from the evidence contained in a thin section of area less than one square inch. In the field, or in larger volume samples, with additional applicable diagnostic criteria, where the seams may be followed in search of critical evidence, the proportion of late-originating to non-diagnosable stylolites is much higher than shown in table I.

Most stylolites classed as not diagnostic of rock condition at the time of origin occur in rocks in which index features (fractures, fossils etc.,) are rare: where index features are related to such seams, hard-rock origin is usually demonstrable.

Similar stylolite seams occurring in a single thin section, or sample, or formation might reasonably be assumed to have similar origins, and proof of post-induration origin for one seam might be taken as establishing with high probability post-induration origin for all. Such assumptive argument has been scrupulously disallowed in preparation of the table, which thus presents data which are excessively charitable towards accounts of origin in pre-induration time.

The most common evidences demonstrating rock removal serve also to demonstrate origin after induration (pl. II, etc.), or origin by interpenetration of or penetration into initially indurated elements (pl. III etc.). This observation is condemnatory of soft rock origin and accounts for a very high proportion of the stylolites noted. Stylolites formed by interpenetration of initially indurated elements (fossils, pebbles, etc.) show all the typical characteristics of normal seams, including the longitudinal column striations, thus invalidating for such examples and greatly weakening for all occurrences the contention of Shaub (1939, etc.) that the striations are due to soft rock extrusion processes.

Due allowance being made for relative orientations of thin or polished section, stylolite, and control features, the amount of rock removal can be evaluated, often with fair accuracy (pl. II, figs. 1, 2, etc.). Amount of rock removal assessed from fracture displacement and similar evidences, is usually somewhat greater than the amount suggested by the length of the longest column.

The ubiquity of microstylolites in the limestone column is apparent from the tabulated data. The total of 15,569 seams in 6,399 thin sections (with a total thin section area representing a column estimated at 1 cm wide and about 150 metres high) affords a quantitative insight into frequency of occurrence. The rarity of seams in the Miocene is striking: the rock samples examined have never suffered very deep burial. Relative rarity of seams in some older formations is probably due to erasure of early-history stylolites by late-history diagenetic processes.

Of the stylolites studied for preparation of the table:

FIG. 2.—Large microcolumn penetrating a nummulite: note small segment of nummulite in downward projecting column at top right. The displaced part of the nummulite has not been pushed ahead of the column, nor does it appear within the column.

FIG. 3.—Intimate interpenetration of initially indurated fossil fragments along a branching seam. The central nummulite is mutually impressed, along complex sutures bearing parallel indentations and projections, into three different orbitoids (top left), several small rotalids (top right), another nummulite (right end), and echinoid plate (bottom left). The seam continues through the matrix. The "fit" cannot be fortuitous. The seam originated in hard rock.

FIG. 4.—Limestone, laminated with organic debris (filamentous algae?), showing sharp terminations of all organic elements at stylolite boundaries, absence of flow-structures within columns, and of evidence of soft rock disturbance ahead of columns. The seams formed by rock removal without mechanical disturbance. Note displacement of calcite veins: the seams formed after calcite sealing of fractures in hard rock. (Composite microphotograph.)

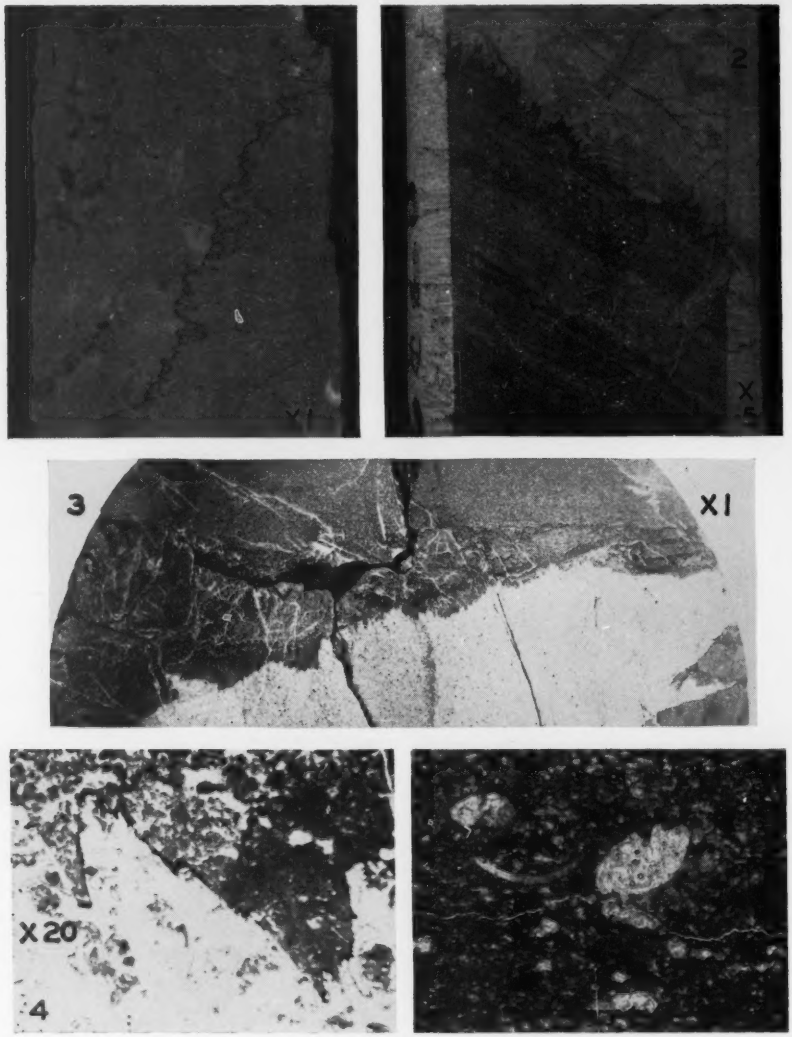

PLATE IV. Stylolites oblique to bedding, etc.

FIG. 1.—Seam bearing almost horizontal columns, cutting limestone breccia. Sample is a well core, natural size, vertical and top and bottom positions as shown. The breccia may have formed before consolidation. The stylolites, consistent in direction through many feet of cores, formed by rock removal after consolidation. Stratal dip is about 25°.

1. all may be explained as originated by solution of hard rock;
2. 79.3 per cent are compatible with origin by solution of rock prior to induration, but beneath the surface of sedimentation, as suggested by Prokopovich (1952);
3. 20.2 per cent could have originated by some such compaction-pressure mechanism as has been suggested by Shaub (1949), in non-indurated rocks.

These relative expressions of compatibility with the various extant theories of origin confirm the qualitative impressions gained from routine observation of an estimated 750,000 seams (mostly microstylolites, since larger stylolites often escape preservation and detection in randomly selected material), scattered through about 300,000 thin sections of limestones of wide age-range, from many localities in the Middle East.

Discounting at this stage the extreme deference paid, in preparation of table I, to the objection of Shaub that penetration of occasional fossils may be fortuitous, and to the feasibility of soft-rock solution producing interpenetration of initially hard fossil content, and also admitting at this stage the probability that all similar stylolites in the same thin section or sample originated in a similar manner and at about the same time, it is concluded that probably all the stylolites seen in material from the Middle East originated after rock induration.

Since the material considered includes a great variety of limestone rock types, differing widely in age and in tectonic history, the extrapolation is ventured that stylolites probably develop only in indurated rocks.

Pending a firmer demonstration than has yet been published that there is a category of stylolites which had their origin in soft sediments, prior to lithification, the statement that all stylolites develop by interpenetration of hard-rock masses due to rock removal in solution is accepted as a working basis for further consideration of other facets of the stylolite topic.

THE MODE OF STYLOLITE ORIGIN

The "solution-pressure theory" of origin (Stockdale 1922, 1943, etc.) recognizes that hard rock is removed during the formation of stylolites, that the removal takes place by solution, with deposition of insoluble residues *in situ*,

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FIG. 2.—Well core, half natural size, showing prominent stylolite seam, slightly inclined to bedding, separating conglomeratic and laminated limestone units. Laminae below the seam at top left are absent due to rock removal at right centre. The prominent seam intersects and displaces earlier stylolite seams which are almost perpendicular to bedding. A thin calcite seam (bottom right) is also terminated at the main seam. The early seams originated after induration as a reaction to tectonic compression: the prominent seam developed still later, but before late Tertiary folding.

FIG. 3.—Conglomerate, with black and white limestone pebbles, cut by seam perpendicular to bedding, with columns parallel to bedding. The seam delimits the upper edge of the white pebble in the photograph, passing into dark limestone matrix at the edges of the core. The seam is one of the early stylolites shown in Fig. 2; the pebbles were indurated before inclusion in the conglomerate. The stylolites formed after consolidation of the conglomerate.

FIG. 4.—Detail of stylolite seam cutting across bedding and juxtaposing rocks of entirely different lithology. Section normal to bedding, long edge of photograph parallel to bedding. The seam cuts lamellibranchs, gastropods, and internal moulds of macrofossils and microfossils in the lower rock unit, and passes indiscriminately from hard fossil fragments into matrix. Stylolite origin postdated crystallization of internal molds.

FIG. 5.—Swarm of stylolitic laminae in argillaceous limestone. The laminae appear in thin section as dark carbonaceous-looking wisps. Stylolitic nature is apparent only where columns are developed in calcitic inclusions. (Microscopic columns in cristellarid, at mid-centre, and in Globotruncana test at bottom centre, are related to two wisp laminae running horizontally across the photograph.)

and that the solution is localized and directionally controlled by pressure. So many observed facts demand acceptance of one or more or all of these tenets that they must be accepted as essentially correct, and a fair statement of the nature of the processes involved in stylolite development. The processes control the characteristics which are available for direct observation, and apart from probable misunderstandings of evidence such as those publicized by Shaub and criticized earlier herein, it is unlikely that any objection can be brought against the argument that development occurs by their operation. (If there is a separate class of stylolites in development of which these processes have not taken any essential part, this must be excluded from consideration here: no unequivocal evidence has yet been brought to confirm the existence of any such class of stylolite.)

Recognition of the processes involved in a phenomenon is not in itself understanding of the phenomenon, and it remains to enquire how satisfactory is the *explanation* of stylolite development.

According to Stockdale (1943, pp. 3–4):

> "Stylolites develop from differential chemical solution in hardened rock, under some pressure, on the two sides of some parting (such as a bedding plane, lamination plane, suture, or crevice), the individual portions of the one side fitting into the dissolved out parts of the opposite, the interfitting taking place slowly and gradually as solution continues."

Stockdale argues that zones of differentially soluble limestone distributed laterally along both sides of a parting subject to solution would soon produce an undulating parting; subsequent pressure would be greatest at the crests and troughs of the undulations and least on the sloping sides "since pressure is important in increasing the solubility of certain solids in liquids the rock opposite the top and bottom surfaces of adjacent undulations will succumb to a greater rate of solution, producing (a) a deepening of the interpenetrating parts, (b) a further decrease in pressure (and consequent dissolving of the rock) on the sides of the undulations, and (c) a possible final development of vertical columns with a decided concentration of pressure and accompanying solution at the ends" (Stockdale 1926, pp. 402–3).

The writer finds difficulty in following the progression of this supposed mechanism of origin. Granted an originally undulating parting subject to solution, and some differential solubility of rocks distributed along it, without the effect of pressure an irregular development of cavities of height controlled by differential solubility would result. The effect of pressure would presumably be to cause accelerated solution at points where opposed surfaces were in contact, thus broadening such surfaces to the point where pressure was equalized over the entire seam. Granted an undulating surface where pressure and solution were originally greater at the crests and troughs, operation of solution at these points would immediately reduce pressure; granting continued solution at crests and troughs the opposed sides of the parting at these points would cease to be in contact and the greatest pressure would occur along the sloping sides, where contact would be made. Shaub (1939, p. 50) registers a similar objection, and notes that "for the process to operate continuously there would have to be a constant rejuvenation of the identical pressure pattern."

The account of Stockdale suggests that the plan-form and dimensions of the stylolite columns are largely determined by the areal distribution against the original seam of materials of slightly different solubilities. Yet incipient serrate stylolite seams of microscopic proportions, and with only minute traverse due to rock removal, appear unrelated in place to visible physical discontinuities which strongly suggest differential solubility (e.g. shell fragments and argillaceous matrix of many limestones) whilst

well developed columns are often situated within single calcite crystals which must be considered chemically pure and physically homogeneous in the limited volumes concerned (pl. II, figs. 1 & 2). Moreover the application of the Riecke principle to the problem invokes multiplied solubility at points of stress which must completely outweigh the initial solubility differences within normal limestones. Again, Stockdale infers that a stylolite column, once determined in areal dimensions, tends to retain the initial plan, or to be diminished in area as its length increases, whilst the impression the writer has gained from this work suggests that minute serrations develop into typical columns of microscopic dimensions which in turn develop by some unexplained amalgamation process into large columns of macroscopic size.

Whilst Stockdale's explanation of the precise mode of origin of stylolites is regarded as inadequate, no alternative account is suggested at this time. It is merely claimed that stylolite seams develop by differential solution of rock after induration, under some uninterpreted control by rock pressure, and that the development involves physical movement by interpenetration of rock masses on opposite sides of the seam.

Pressure Direction and Column Orientation

It is axiomatic that movement of substantial rock masses into one another by penetration must be in a direction parallel to the rock pressure at the time of origin. Anomalous pressures occasioned by rock inhomogeneities may be effective locally, but in general, the directions of pressure, of interpenetration, of column axis orientation, and of longitudinal striation must all be parallel. Many useful applications of this axiom are possible (Shrock, 1948, pp. 234–241). Thus (assuming effective rock pressure to be vertical) if column axis departure from vertical is subtracted from present structural dip (with due regard to azimuthal orientation where necessary and possible) the structural dip at the time of stylolite development can be derived. If the history of dip development is known, as is often the case in drilled-up anticlinal oilfields, the precise geological time of stylolite origin may be determinable. Alternatively, in lesser known structures, if the time of stylolite development can be accepted from external evidence, the local structural dip at that time can be inferred. Such applications have been attempted with variable but significant success on borehole cores, and even on rotary bit cuttings from wells; in the field they provide valuable evidence for derivation of tectonic histories.

Blake and Roy (1949) have shown that seam and column orientation may be directionally controlled by lateral tectonic compression, which may completely outweigh the vertical pressures due to overburden load. Plate IV, figure 1 illustrates a similar occurrence of more limited scope. The structural dip at the point at the point of origin of the figured core is about 25°, and it can be fairly safely asserted that it has never been greater than this value. The columns are oriented at only 5° to the horizontal. If the stylolites originated before the folding the effective pressure must have operated along planes dipping not more than 30° from the horizontal; that is the tectonic compressional pressure must have exceeded the overburden pressure by a factor of at least 2:1.

Nature of the Solvent

It is generally inferred that the waters responsible for stylolite solution are downward percolating surface waters charged with carbon dioxide in solution, and unsaturated. Whilst some stylolites may have formed through solution by such waters it is clear that many important occurrences in the Middle East are found in a geological setting which precludes the possibility of surface waters ever having entered the system after induration. In these cases it must be admitted that the solvent available for stylolite generation must have been con-

nate water, already saturated with any soluble material occurring in the beds in which it existed. Hence it must be assumed that the stylolites are the consequence of local supersaturation occasioned by local high stresses, invoking the "Riecke principle" in one or another of its multiple guises.

Supersaturated solutions cannot persist indefinitely, and the excess calcium carbonates must be deposited shortly after supersolution in whatever voids happen to be available for deposition. In the normal case of an initially porous limestone it is to be presumed that calcium carbonate dissolved during development of the stylolites will redeposit within the accessible pore spaces, wherever a suitable crystal face is presented as a crystallization nucleus. The same saturated solvent might have functioned innumerable times as a vehicle for transport of material from the scene of solution into the pores of the rock mass. The tight semilithographic character of many limestone units in which stylolites are well developed strongly supports the suggestion that redeposition of dissolved material occurs almost *in situ*, and that stylolite development continues until original porosity is almost obliterated.

Stylolites and Oil Migration

R. M. Ramsden has drawn attention to the fact that stylolites of "pressure solution" type infer net compaction of the rock due to actual removal of rock substance. He cites the estimate by Stockdale (1946) that stylolites have reduced the thicknesses of some limestone units by as much as 40 percent, and remarks:

> "It is certain that if 40 per cent of the rock is removed from the section 40 per cent of the contained fluids must be simultaneously released. These fluids must necessarily undergo lateral migration as the overburden causes subsidence to occur within and above the limestone in which solution has taken place" (Ramsden, 1952).

The percentage volume of fluids displaced purely by stylolitic interpenetration will be almost exactly equal to the percentage thickness reduction in section, so that where this last is small it would appear that the migrations occasioned must also have been small. But if the argument of the preceding section be admitted, large reduction of thickness is not necessary in order to expel a very high proportion of the contained fluids from a porous limestone. If a water-wet pure limestone, initially of 10 per cent porosity be reduced in thickness by 10 per cent by stylolite development, 10 per cent of the contained fluids will be expelled, but if the solvent was originally saturated, and if redeposition from supersaturation takes place entirely within the limestone itself, the pore voids of the remaining 90 per cent of limestone will be infilled, and the *entire* fluid content will be expelled. The same consequences would ensue if the initial porosity was 40 per cent (or 1 per cent) and the thickness reduction was 40 per cent (or 1 per cent). Complete obliteration of porosity will never be achieved, since penetration of supersaturated solution into the rock mass becomes more difficult as the process continues. Eventually, where stylolite development continues, excess calcium carbonate in supersaturation must pass out of the system via the stylolite seams themselves (the only remaining channels for fluid movement), to be redeposited with reduction of porosity in some other (usually higher) location.

The suggested processes are closely comparable with those of porosity reduction and cementation in sandstones, the vital relationships of which to oil migration and accumulation have been dealt with by Waldschmidt (1941).

Other factors being equal, stylolite development must commence earliest and pass to completion soonest where the rock pressure is greatest, that is where the overburden is greatest. If there is no tectonic interference, section thinning by stylolitic penetration and elimination of porosity by reprecipitation will commence in any unit where the overburden is great-

est and will develop progressively in directions in which overburden pressures diminish.

Other factors being equal it would appear that there must be a critical rock pressure below which stylolites cannot form, and above which they must. This necessity is merely a vague and theoretical one, but it is supported by the finding that in the more recent or never deeply buried formations studied in the Middle East, stylolites are rare, whilst in single formations stylolites are found in increasing abundance in rough proportion as they have been subjected to increasing overburden. Other factors, which must in fact vary, render difficult any investigation of the significance of overburden, and any attempt to determine the critical pressure value (if such exists). Temperature relates directly to overburden, and is thus a factor sympathetic with rock pressure, from which it need not be separated at this stage of enquiry. Chemical attributes of connate waters offer little differentiation within single enclosed aquifers in many subsurface areas under consideration, though they will clearly vary with both temperature and pressure, and may have been very different in the past. Differences in lithology must also have an effect, but the habits of known stylolites do not include careful selection of particular grade or crystal sizes, or avoidance of any particular type of limestone. Investigation of a very large number of stylolite histories would be necessary before any clear evaluation of the different factors could be attempted. Experimental approach, involving application of variable pressure to controlled rock and solvent systems under controlled hydrostatic pressure and temperature could produce a better quantitative evaluation, but no published results of really significant experiments have yet been encountered in a not very exhaustive scanning of recent literature. For the present it is accepted that the concept of a critical pressure necessary for stylolite genesis holds for any individual limestone formation which does not vary laterally in lithology beyond the extremes that single stylolite seams are known to tolerate in heterogeneous limestones, and in which it can be presumed that the water is chemically similar.

The concepts of fluid expression by stylolite development and associated porosity elimination following attainment of a critical overburden pressure have obvious potentials in application to oil migration problems. Considering a simple situation where a thick euxinic "source bed" shale sequence in a rapidly subsiding basin passes laterally into widely extensive thinner platform-type porous limestones of oolitic or biostromic character under an impervious cover, and where subsequent deposition continues thickly in the basinal area and more thinly towards its margins, it is clear that fluid migrations will be controlled by two dominant processes. The initial process of normal compaction of shales under load will compel most of the contained fluids (including oil) of the source beds to pass into the porous limestones, where further concentration of oil will be dictated by stratal gradients and intrinsic porosity. The slow tempo of compaction in the basin will not usually provide sufficient fluid flow to dislodge any involved oil from the first-encountered porous sections in which it can find accommodation, so that unless high gradients occur to assist further movement, initial accumulations of oil will be situated usually in the higher parts of porous sections near to the basinal source. Compaction in the basin will be continuous but continuously diminishing, and eventually will cease to have great significance as a motivating process of fluid migration. Should structural differentiation take place at this stage productive structures may be largely confined to the zone where porous limestones and source beds are juxtaposed. If no structure develops at this stage the initial oil accumulation will remain in this zone unless and until the increase in basinwards dip consequent upon further

depression in the basin promotes marginwards migration by gravity drive; the effectiveness of such drive will be dependent largely upon the extent, nature and distribution of porosity within the limestone mass. But as overburden increases, the critical pressure for stylolite development under prevailing salinity, temperature, and hydrostatic conditions will be reached, and expulsion of all contained fluids from water-wet porous limestones will commence, passing outwards and upwards from the zone of initial accumulation, towards the basin margins. Connate water, supersaturated at depth, will deposit mineral pore-fillings in its upward passage as hydrostatic pressure is reduced, thus amplifying the marginward drive occasioned primarily by pressure-solution effects. The geographical endpoint of the process will be approached where the overburden is inadequate to promote significant stylolite development; secondary oil accumulations must then be sought in a zone surrounding but generally marginward of the line of critical overburden.

It seems probable that if sufficient oil accumulates in any area to produce oil-wetting of the limestone pore surfaces, the depositional process will be halted by inhibition of recrystallization from supersaturation, owing to inaccessibility of crystal nuclei. Also if oil has anywhere congregated to the exclusion of water, development of stylolites will be there prevented. Isolated accumulations of oil may thus be anticipated basinwards of the zone of critical overburden, possibly surrounded on all sides by stylolitized, densely recrystallized, non-porous limestone; anomalous reservoir pressures may exist in such reservoirs, and hydrostatic water drive may be absent. Failing some inhibition of recrystallization, it seems that below the (hypothetical) critical depth, useful porosity must be entirely eliminated from limestones (and at variously lower depths from various other rocks). Thus an upper limit is suggested below which search for oil should become search for localized conditions favoring such inhibition. Oil itself is the only significant and effective inhibitor that comes readily to mind; presence of oil in bulk will forbid stylolite development, whilst oil-wetting of surfaces will check recrystallization; it is also possible that oil bodies may automatically increase the porosity of their immediate surroundings and discourage stylolite development and cementation by local modification of the chemical attributes of the associated waters (cf. Van Tine, 1945, p. 34).

In some cases stylolite development and associated cementation may have operated thus to preserve early oil accumulations in place, and to prevent migration into later forming and more readily discerned structural or other traps.

The search for deep oil in limestone reservoirs may resolve itself into enquiry as to the position of probable oil accumulations at the time of stylolite formation, whilst the time of stylolite formation will relate to the attainment of critical overburden and may vary locally as well as from basin to margin.

Without pursuing the further ramifications of the topic, it is for the present merely emphasised that stylolite development and associated pore reduction by precipitation (or, of course, either process without the other) can produce ideally localized forces adequate to expel the contained fluids from water-wet pore-spaces and to impel them up-dip from basinal to marginal areas and from syncline to anticline. The processes can be effective even where the dip is quite inadequate for gravitational migration, and they are many times more potent than hydraulic drive due to distant compaction. The processes are adequate for displacement of water-entrained oil from the low permeability temporary reservoirs which are presumable adjacent to the source, and in which much oil would remain if gravity or slow fluid movement or capillarity were the sole forces urging migration upwards.

Significant in the thesis is the *time* at which the processes are deemed to occur. Stylolite development, if related

in fact as well as in theory to critical overburden (or overburden-plus-tectonic) pressure, must be a late-history phenomenon, becoming of importance as a fluid mover probably at the stage when shale compaction is dwindling into insignificance. The literature of petroleum geology is replete with bewilderment (and with unconvincing accounts) as to the mechanism by which oil accumulation can have occurred after significant hostile events (erosion of reservoir, formation of transient intermediate traps, injection of igneous materials, reversals of gradient, etc.) which bridge the period during which compaction of presumed source rocks and other processes favoring migration can be regarded as operative. Stylolite development and entailed precipitation in limestones, and grain reduction and entailed precipitation in sandstones (Waldschmidt 1941) provide "delayed-action" mechanisms which can be invoked to explain such improbable oil accumulations.

Whereas suture formation in sandstones is apparently a rarity (Sloss and Feray, 1948), usually outweighed in significance by normal sand compaction and cementation processes, and probably only rarely of fundamental significance as a motivator of fluid migration, stylolites are so widely distributed and involve such large rock-volume adjustments in most limestones that the fluid migrations occasioned by the stylolite-making processes must frequently have outweighed in significance fluid movements attributable to all other causes.

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SOME CHARACTERISTICS OF SOUTHERN CALIFORNIA SEDIMENTS[1]

K. O. EMERY
University of Southern California

ABSTRACT

Average median diameters, sorting coefficients, and contents of calcium carbonate and organic matter were compiled for several thousand sediment samples belonging to 21 different land and sea floor environments of southern California and adjacent Mexico. Comparison of the results shows that these parameters are interrelated and dependent on the physical-chemical conditions of deposition.

INTRODUCTION

During the past half century many thousands of textural analyses of sediments have provided information on local variations of sediment within individual environments. A broader use of sediment analyses is the characterization of different environments. This objective was recognized by Udden (1914), who approached it by tabulating the percentage weight distribution of grain sizes for 371 samples taken from the sea floor, beaches, dunes, till, soil, and miscellaneous sources. Wentworth (1932) combined Udden's analyses with others into a series of histograms for a total of 828 samples. Still later, Doeglas (1946) brought together analyses of about 112 samples mostly from Netherlands sources in the form of cumulative curves plotted on arithmetic probability paper. For many general purposes, however, the information presented by histograms and cumulative curves can be expressed sufficiently well by the simpler parameters—median diameter and sorting coefficient. In addition to texture, the contents of calcium carbonate and organic matter may serve to characterize different kinds of sediment as pointed out by Trask (1932) who presented many such analyses.

Analyses of more than 3500 sediment samples from various environments of southern California and adjacent Mexico are now available, largely due to studies made during the past decade. These serve as the basis for table 1, in which values are averaged and where necessary weighted as described below to balance different studies within the same environment. The process of weighting reduced the total to about 2600 analyses.

Textural characteristics are expressed herein only as median diameters and sorting coefficients, $So = \sqrt{Q_1/Q_3}$. Gravels were excluded throughout because in many deposits they appear to form a clearly separate secondary maximum; also, good analyses that include gravel are rare. Values of calcium carbonate were mostly percentage weight loss after treatment of a sample with dilute acid, though some were computed from measurements of carbon dioxide driven off by acid treatment or of calcium present in the acid-soluble fraction. Values for organic matter were about equally divided between determinations of total organic matter by weight loss during treatment with hydrogen peroxide and determinations of organic carbon or nitrogen by various methods. Total organic matter in the latter samples was estimated by multiplying the percentage of carbon or nitrogen by an appropriate factor.

It must be emphasized that table 1 cannot be used as a reliable basis for de-

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TABLE 1.—*Characteristics of sediments from various environments*

Environment	Median Diam. (microns)		Sorting Coefficient		$CaCO_3$ (%)		Organic Matter (%)	
Coastal Soils	80	*109*[1]	3.1	*109*	0.4	*109*	1.5	*est.*
Mudflow	840	*10*	3.8	*10*	0	*est.*	0.0	*est.*
Cave Dust	500	*4*	11.0	*4*	43	*4*	0.5	*est.*
Meteoritic Dust	31	*1*	1.5	*1*	0	*1*	0.0	*1*
Playa Lake Floors	4.0	*25*	5.0	*25*	15	*25*	0.2	*10*
Perennial Lake Floors	3.2	*43*	3.9	*4*	12	*42*	2.1	*43*
Stream Beds	610	*44*	2.0	*30*	1	*est.*	0.0	*est.*
Stream Loads	46	*50*	2.2	*78*	9.5	*34*	0.0	*est.*
Dunes	260	*52*	1.3	*52*	0.7	*8*	0.1	*4*
Marshes	32	*149*	4.2	*149*	1.2	*79*	18	*91*
Beaches	350	*111*	1.3	*85*	7.1	*21*	0.0	*1*
Mainland Shelves	140	*1409*	1.6	*454*	13	*201*	0.8	*22*
Island Shelves	150	*61*	1.8	*61*	18	*5*	0.3	*38*
Bank Tops	270	*284*	2.3	*164*	56	*166*	0.8	*146*
Strait	1000	*50*	1.9	*50*	60	*50*	0.5	*est.*
Basin Slopes	54	*57*	2.7	*31*	18	*33*	2.8	*30*
Pliocene Shales of Los Angeles Basin	14	*24*	3.9	*24*	4.9	*24*	2.6	*24*
Basin Floors	3.5	*65*	3.8	*33*	23	*13*	7.5	*12*
Continental Slope	9.2	*5*	4.2	*5*	27	*5*	4.2	*5*
Globigerina Ooze	9.2	*6*	6.2	*6*	78	*31*	0.7	*19*
Red Clay	1.3	*9*	2.7	*8*	3.8	*26*	1.9	*10*
Totals		*2568*		*1383*		*877*		*456*

[1] Italics indicate number of analyses on which each average is based.

termining the probable environment of deposition for a given sample. The table merely lists the average values of several parameters for different environments of southern California. In each environment there is considerable variation. Under different climate or source conditions, either present or past, the parameters may well be different. Their true effectiveness for characterizing environments can be determined only after similar compilations have been made for other regions and all are compared.

SOURCES OF DATA

Coastal Soils

Most of the data for southern California coastal soils were obtained from soil surveys by the U. S. Department of Agriculture (Carpenter and Storie, 1929; Nelson, Dean, Kocher, Watson, and Carpenter, 1920; Nelson, Zinn, Strahorn, Watson, and Dunn, 1919; Storie and Carpenter, 1929 and 1930). These reports contain tables of the distribution of grain sizes in 109 samples of fifty soil types. Median diameters and sorting coefficients were computed and averaged after being weighted according to the aerial extent of each soil type. Calcium carbonate was estimated from data given in the same reports, and a very approximate figure for organic matter was assigned on the basis of general information on the organic content of similar soils (Schreiner and Brown, 1938) supplemented by a few unpublished analyses in the files of the Sediment Laboratory of the University of Southern California. Because of the wide range of soil types (clays to sands) the various parameters have a larger variation than in other types of sediment. Many of the soils are immature types so their characteristics are inherited from the substrates.

Mudflow

A description of a 15-mile mudflow down the north side of the San Gabriel Mountains by Sharp and Nobles (1953) included cumulative curves and textural data for ten samples. The contents of calcium carbonate and organic matter are presumed to be negligible.

Cave Dust

Although cave dusts are of minor areal importance, some data for them are included from analyses reported by Emery and Easton (1951) for dust in a limestone cave of the Mojave Desert. The dust is a natural concentrate of insoluble residue of the limestone. The large median grain size and poor sorting results from the presence of fragments of limestone and slightly less soluble fossils that had fallen into the dust after being loosened by solution of the matrix.

Meteoritic Dust

Like the cave dust, meteoritic dust is quantitatively unimportant but nevertheless interesting. Diameters of nearly 2500 individuals grains of meteoritic dust collected near Pasadena were measured and tabulated by Buddhue (1950). After conversion to weight basis these measurements yield the median diameter and sorting coefficient given in table 1. About four-fifths of the grains are black magnetic metallic ones and the others are silicates.

Playa Lake Floors

Data for the sediments comprising the floors of playa lakes were obtained from Stone (1952). He grouped playas into two major types: dry and moist. Sediments of both types are similar except for their water and salt content, so the values shown in table 1 are based on averages of about 100 samples from 25 playas of both types. In general, the largest playa lake floors consist of the finest sediment, even down to 1 micron median diameter. Characteristically, the sediment in any given playa is fairly uniform from one side to the other. The edge of each flat basin, however, is generally marked by a narrow band of coarser sediment that was deposited by streams at the change of gradient or was winnowed at a former shoreline.

Perennial Lake Floors

Surveys have been made of the sediments of several perennial lakes in the region. The most complete study is for Lake Mead (Gould, 1953), of which only the flat-lying deposit beyond the foot of the main delta is considered here. Other data came from Lake Elsinore (Mann, 1951) and from the very small Baldwin Lake (Emery, in press). The grain size was found to be inversely proportional to lake area and the organic content of the Lake Mead sediments was only one-fifth that of the other two lakes, probably owing to its much greater rate of deposition of clastic sediments. In each of the lakes the sediment was nearly uniform across the entire floor. Only near the shore or on underwater hills is there any appreciable coarsening.

Stream Beds

Median diameters and sorting coefficients of 21 streams between Ventura and Redondo were taken from a report by Handin (1951) and for 9 others from an unpublished study of the Rio Hondo River by Vernon Rutherford in the U. S. C. Sediment Laboratory files. Median diameters of 14 other sandy stream beds between Ventura and Point Conception are given by Hunter (1948). No measurements of calcium carbonate or of organic matter were included and the figures given in table 1 for these parameters are only rough estimates based on general information. All analyses were made on surface portions of the stream beds near the ocean. A larger grain size would have resulted if samples nearer the headwaters had been used.

Stream Loads

Total sediment carried by streams (not that remaining on the stream beds) is

among the least satisfactorily reported of all the sediments in table 1. Owing to lack of data for coastal streams, most of the information was taken from a study of the sediments brought by the Colorado River into Lake Mead (Gould, 1953). Sampling of the delta and the lake floor provided a reasonably good means of estimating the median diameter of the whole load that was carried by the river during a period of 14 years. This value, 46 microns, is qualitatively supported by some measurements of suspended sediment in the larger coastal streams (Revelle and Shepard, 1939) which yielded a median diameter of 20 to 35 microns. Based on total sediment deposited in Lake Mead, during all stages of discharge, the sorting coefficient was found to be much higher (8.0) than would be expected of river-borne sediment that is sampled at any given instant. Therefore, an average sorting coefficient was computed from 78 analyses of suspended sediment of the Colorado River selected on a monthly basis from amongst about 500 analyses presented by Howard (1947) for the period 1935–41. Calcium carbonate content of the total deposits in Lake Mead is almost identical with the figure of 10 per cent reported by Sykes (1937, p. 133) for suspended sediment in the Colorado River.

Dunes

Data for the characteristics of dune sands were taken largely from studies by Eymann (1953) and Stone (1952) of sands from 35 dunes of the Mojave and Colorado Deserts. Sands of 6 coastal dunes are reported by Handin (1951), and, in an unpublished study by the U.S.C. Sediment Laboratory, J. F. Gale described 13 samples from a single coastal dune which for this report are weighted as 3 samples. In addition, 40 analyses of Pleistocene dune sands of Santa Monica by Merriam (1949) are given a relative weight of 5 analyses, and 47 analyses of Pleistocene dune sand beach ridges of San Diego County by Emery (1950) are given a weight of 3 analyses. Calcium carbonate determinations are available for only the Pleistocene dune sands. Measurements of organic matter were reported by Eymann (1953) for 4 dunes, 2 of which were partially covered by vegetation. Where sufficiently detailed the studies show that the dunes are coarser grained on the windward edge than on the crest and lee slope.

Marshes

An intensive study of the marshes at Newport Bay was made by Stevenson (in preparation). In the study are many sediment analyses that show the presence of sands on the beaches and in the tidal channels, but chiefly silts and clays on the extensive flat areas that are covered by marsh vegetation. Only the latter are included in table 1. The vegetation supplies a large amount of organic matter that partly remains in the sediment and partly decomposes, producing organic acids that have led to leaching of the calcium carbonate that is contributed by shells.

Beaches

Many studies have been made of beach sediments in the region, but few are very complete from the viewpoint of over-all sediment characterization. The best published general textural study is one by Handin (1951) for beaches from Ventura to Redondo. Average median diameters and sorting coefficients based on his several hundred analyses at 68 localities are included in table 1. Six small published and unpublished studies mostly covering areas south of Los Angeles provided 43 more textural analyses. Other data on median diameters could have been included but they would have unduly weighted small portions of the coast. Values for calcium carbonate and organic content were derived chiefly from studies of beaches near La Jolla (Inman, 1953), of Coronado Strand south of San Diego (Emery, Butcher, Gould, and Shepard, 1952), and of Vizcaino Bay in Mexico (Gorsline, in preparation) but they are

probably fairly representative of the rest of the coast. In general the smaller beaches are coarser and most are coarser on the foreshore than on the backshore.

Mainland Shelves

The bulk of the data for the narrow continental shelf came from a report by Emery, Butcher, Gould, and Shepard (1952) on the sediments off San Diego. From this area are 1105 samples from the shelf (excluding Coronado Bank), mostly taken by clam-shell snapper. Data for 135 dredge and clam-shell samples from the shelf off Santa Monica were taken from laboratory notes on which Shepard and Macdonald (1938) prepared a brief report on that area. An additional 76 clam-shell samples from the shelf off San Pedro were described by Moore (1951). From other shelves of the region Garrison and Takasaki (1950) reported 24 analyses, Dana (1942) gave 7 analyses, and Trask (1932) 5 others. Although not strictly from southern California, data for 57 samples from Vizcaino Bay, Mexico (Gorsline, in preparation) are also included because of the climatic similarity of the regions. The average depth of all samples is about 200 feet. Average values of median diameter, sorting coefficient, calcium carbonate, and organic matter for samples from all areas are given in table 1. Sediments of the shelf are of complex origin as described by Emery (1952), consisting of organic, authigenic, relict, and residual materials only partially overlain by present-day detrital sediment. The former types are concentrated at the outer edge of the shelf and on hills that rise above the general level of the shelf, wherever currents prevent the accumulation of present-day detrital sediment.

Island Shelves

The most general study of island shelf sediments is that of Dana (1942) who analyzed 33 samples dredged offshore of most of the islands. The distribution of sediments on the shelf off Catalina Island is reported by Shepard and Wrath (1937) and study of their laboratory notes yielded 20 unpublished mechanical analyses. Data for 6 additional short core samples from off various islands were reported by Garrison and Takasaki (1950) and 2 others are described by Trask (1932). The average depth of all samples is about 200 feet. Sediments of the island shelves are of the same varied origins as those of the mainland shelf, but, because streams on the islands are small, present-day detrital sediment is less abundant than on the mainland shelf.

Bank Tops

Much of the data for bank top sediments came from Coronado Bank off San Diego (Emery, Butcher, Gould, and Shepard, 1952). Uchupi (in preparation) also contributed heavily to the information on the bank top environment with 95 analyses of texture, calcium carbonate, and organic matter. Fifty samples from Cortes and Tanner Banks (Holzman, 1952), 11 from Ranger Bank (Emery, 1948), and 8 from various other banks in the region (Dana, 1942) also provided information for table 1. The average depth of all the samples is about 400 feet and few are from deeper than 600 feet. Practically all are spot surface samples taken with a clam-shell snapper. On each of the banks the sediment is dominantly of organic origin—foraminiferal and mollusk shells—with authigenic and residual constituents next in importance. Coarsest sediments of highest calcium carbonate content and lowest organic matter occur on the shallowest portions of the banks.

Strait

No important shallow strait occurs in the area off southern California, but Kellet Channel that adjoins Vizcaino Bay in Mexico is in a similar climate and is included herein. Gorsline (in preparation) analyzed 50 samples collected by the writer from an average depth of about 100 feet. The coarse grain size, good sort-

ing, and high calcium carbonate (table 1) is a result of high concentrations of shell fragments and calcareous algae in the current-swept channel.

Basin Slopes

The slopes that form the sides of the basins have been given no systematic study; however, some analyses have been made in connection with other work. Textural data for 25 cores and surface samples collected mostly by F. P. Shepard are summarized by Garrison and Takasaki (1950). Similar data plus organic content are given by Dana (1942) for 8 dredgings. Measurements of calcium carbonate and organic content are listed by Trask (1932) for 31 samples, for 24 of which he presented textural data. The average depth of all samples is about 3000 feet. Basin slope samples are characterized by wide diversity probably resulting from landsliding, as suggested by the fact that core samples generally consist of only a thin layer of sediment atop bedrock. Photographs of one slope show it to have a 40° declivity, and soundings indicate that others are fully as steep.

Pliocene Shales of Los Angeles Basin

The sediments in the completely filled Los Angeles Basin were described and compared with those of the partly filled basins of the sea floor by Emery and Rittenberg (1952). Between depths of 150 and 6030 feet in the Dominguez oil field 24 samples of Pliocene shales present a gradual and irregular decrease of grain size with depth (age). Thin interbedded sands are common, probably having been deposited by ancient turbidity currents, but they are omitted from table 1. These results are qualitatively supported by a parallel study by Trask and Patnode (1942) in which different units were used, and by unpublished reports in the files of the U. S. C. Sediment Laboratory. The Pliocene shales are similar to the sediments of the sea floor basins nearest shore, and the Los Angeles area is evidently the site of one of those basins that became filled to above sea level.

Basin Floors

The characteristics of sediments that cover the floors of the submarine basins between the coast and the continental slope were taken mostly from a report on this environment by Emery and Rittenberg (1952). Cores from each of 12 basins were divided into 10 to 25 sections that were analyzed separately but were averaged together for table 1. Thus, the median diameter, sorting coefficient, calcium carbonate, and organic matter at these 12 sites are based on 200, 200, 154, and 157 analyses respectively. Additional median diameters and sorting coefficients were taken from 53 other cores collected mostly by F. P. Shepard during 1937–8 (Garrison and Takasaki, 1950) and by Trask (1932). The average depth of all samples is about 4000 feet. In general, the grain size decreases from basin to basin in an offshore direction, with the coarsest sediment having the lowest calcium carbonate and organic matter occurring in the basins located closest to shore. Calcium carbonate increases steadily with distance from shore. Grain size decreases outwardly except for the outermost basins where the high concentration of foraminiferal tests gives rise to an increase of grain size in the total sediment. Organic matter is highest in basins at intermediate distance from shore owing to masking by rapidly deposited detrital sediment in basins nearer shore and to destruction before very slow burial in basins farther offshore.

Continental Slope

Analyses of only 5 cores from the continental slope are available. Four of these are part of a series taken by Dill (1952) across the shelf and slope off Point Conception; the other is a core described by Emery and Rittenberg (1952). The cores were divided into 4 to 15 sections each and the sections were analyzed separately, though for this summary only the aver-

age for all sections of each core was used. The average depth of all cores is 5000 feet. Characteristically, the sediment from the continental slope off California is thin and underlain by bedrock. As a result, it seems probable that the sediment, like that on the basin slopes, is not very stable and is subject to frequent landsliding that should obscure any original relationships of the sediment to depth.

Globigerina Ooze

All data for deep-sea globigerina ooze were taken from a report by Revelle (1944) on deep-sea sediment of the Pacific Ocean collected aboard the *Carnegie*. For 31 samples taken by clam-shell snapper and short corer the average depth is 11,000 feet. The calcium carbonate content in these particular samples averaged 78 per cent, but globigerina ooze may have a wide range of values that are related to depth and to geographical position relative to currents. It is distinguished from red clay chiefly on the basis of containing more than 30 per cent of calcium carbonate, composed mostly of pelagic Foraminifera.

Red Clay

Most of the information on deep-sea red clay was taken from Revelle (1944) for samples throughout the Pacific Ocean. Some data for a single long core taken by F. P. Shepard in 1938 about 70 miles beyond the continental slope off California are also included. The average depth of the 27 clam-shell snapper and core samples is 15,500 feet. Red clays consist of the more insoluble portions of pelagic sediment, mostly land-derived clays, and there is little dependence of grain size on distance from shore.

CONCLUSIONS

Median Diameter

Median diameters are within the sand range for most of the environments of table 1: straits, mudflow, stream beds, cave dust, beaches, dunes, bank tops, island shelves, mainland shelves, and coastal soils. Those for Basin slopes, stream loads, marshes, meteoritic dust, Pliocene shales of Los Angeles Basin, continental slope, and globigerina ooze are within the silt range, while those for playa lake floors, basin floors, perennial lake floors, and red clay are in the clay size range. The median diameters given in the table are only averages. Values for individual samples of any given environment may vary widely; nevertheless, the averages show certain relationships between different environments.

The total load carried by streams in suspension and traction is somewhat finer than the soils which serve as the chief source material, suggesting that winnowing action has occurred. The coarsest sediment that can be carried forms the stream beds. Locally, stream-borne sediment is trapped in lakes, the central areas of which are reached by only the finest sediment. Elsewhere the streams contribute sediment to the ocean. Most of the coarser part of the stream contribution evidently stays on the beaches, whereas the finer constituents are deposited in marshes or are carried across the shelf and into the basins. The increase of grain size from mainland shelves to island shelves to bank tops to strait results, no doubt, from the progressively greater exposure to waves and currents in the latter environments and to the smaller content of detrital sediment as compared to shell fragments. There is a further decrease of grain size from the shelves and bank tops through the basin slopes to the basin floors. The basins closest to shore have the coarsest sediment and this is reflected in the larger grain size of Pliocene shales in the now filled Los Angeles Basin. Farther seaward the continental slope sediments are slightly coarser than the basin floor sediments partly because of a higher content of foraminiferal tests that are larger than the detrital grains in the matrix. For the same reason globigerina ooze is coarser than red clay, which has the smallest average median diameter of all the sediments.

Sorting Coefficient

Average sorting coefficients range from 1.3 to 11.0 with only slight relationship to average median diameters. Using Trask's limits (less than 2.5—well sorted, more than 4.5—poorly sorted) we find that dunes, beaches, meteoritic dust, mainland shelves, island shelves, the strait, bank tops, stream beds, and stream loads consist on the average of well sorted sediment. Basin slopes, red clay, coastal soils, basin floors, mudflow, perennial lake floors, Pliocene shales of Los Angeles Basin, and the continental slope have moderately sorted sediment. Playa lake floors globigerina ooze, and cave dust are poorly sorted. It should be noted that the sorting coefficient for any given environment of table 1 is only an average and that values for individual samples may range from much less to much greater than the average, the spread depending on the kind of environment.

Trask (1932, pp. 71–72) established the well-known limits for the three different degrees of sorting on the basis of 172 analyses of marine sediments. In 25 per cent of his analyses the sorting coefficient was less than 2.5 and in 25 per cent, larger than 4.5. His median sorting coefficient was 2.9. Table 1 gives average sorting coefficients for 1383 analyses, the over-all average of which is 2.4. On the other hand, the average of the average values for the 21 different environments is 3.4. Because of the large difference between these two over-all averages (2.4 and 3.4) it seems evident that the limits between the well to moderate and the moderate to poorly sorted samples should be based neither on an average by number of analyses nor on an average by number of environments. If computed by some method that considers the areas covered by different kinds of sediment, the sorting coefficient would be dominated by red clay and globigerina ooze, even though relatively few samples are ever taken of them. In summary, it seems desirable to drop the use in an absolute sense of the terms *well, moderate,* and *poorly sorted* and to use them only for describing the relative degrees of sorting within a given environment with different limits chosen for different environments.

Calcium Carbonate

The average calcium carbonate content of the coastal soils is low in the surface zone of leaching from which sample data for table 1 were taken. Calcium carbonate has been concentrated in the playa and perennial lake basins mostly by withdrawal from solution as evaporites or shell fragments. The calcium carbonate for stream loads (table 1) is that of the Colorado River, which drains an area of thick limestones; the value for coastal streams is probably much lower, but data for these streams are not available. The progressive increase of calcium carbonate from beaches to mainland shelves to island shelves to bank tops to straits results from seaward increase in percentage of shell fragments owing to a progressively slower rate of deposition of detrital sediments in these shallow areas. Similarly, there is a parallel seaward increase of calcium carbonate in the deep environments: from Pliocene shales of Los Angeles basin to offshore basin floors to continental slope to globigerina ooze. Finally, red clay has a markedly decreased calcium carbonate content owing to resolution in the unsaturated deep ocean waters.

Organic Matter

Fewer data are available for organic matter than for the other parameters, largely owing to the greater difficulty of measurement. For 6 environments the content of organic matter is merely an estimate. The highest content of all (18 per cent) was found in marshes, where there is an abundant growth of vegetation much of which becomes buried in the sediment and preserved. A high organic content also exists in the fine-grained basin floor sediments largely owing to anaerobic conditions at a depth of one or two feet. The slower rate of deposition on

the continental slope and in abyssal sediments results in oxidation and loss of organic matter before burial. Similarly, the shelves, bank tops, and straits have little organic matter because they also are sites of slow or non-deposition of detrital sediments. Conversely, perennial lake basins and the former marine Los Angeles Basin received detrital sediments so fast that organic matter became masked or diluted. The affinity of organic matter for fine-grained sediment is well shown by the higher content of organic matter in red clay than in globigerina ooze. For these sediments, as for others, there is no direct relationship between the content of organic matter and of calcium carbonate.

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ARAGONITE TESTS AMONG THE FORAMINIFERA[1]

ORVILLE L. BANDY
University of Southern California, Los Angeles, California

ABSTRACT

Aragonite has been found composing the tests of a few species of Foraminifera, while the tests of an estimated 1,700 to 2,000 species were composed of calcite. The aragonite apparently is quite stable.

Many authors have reported calcite tests among the Foraminifera in the past (Clarke and Wheeler, 1922; Galloway, 1933; Wood, 1949; and others), but apparently no experimental data heretofore have revealed aragonite. The author's attention was directed to the problem by Dr. K. O. Emery, University of Southern California. While testing some recent sediments for the presence of aragonite with Meigen's reaction, he found that one type of foraminifer (*Höglundina elegans*) gave a positive test. The author selected faunas from the Cretaceous and from most of the epochs of the Cenozoic including recent sediments and checked them with Meigen's reaction (cobalt nitrate test). Most of the faunas were from North America

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TABLE 1.—*Species of Foraminifera which gave a positive reaction for aragonite.*

Species	Stage or formation and location	Age
Höglundina elegans (d'Orbigny)	abyssal zone off Point Arguello, California	Recent
Höglundina elegans (d'Orbigny)	100 fathoms off Tampa, Florida	Recent
Bigenerina irregularis Phleger and Parker (calcareous cement stained)	30 fathoms, northern Gulf of Mexico	Recent
Ceratobulimina stellata Bandy[1]	Lisbon fm., Alabama	Eocene
Pseudobulimina glaessneri Howe and Roberts	Lisbon fm., Alabama	Eocene
Ceratobulimina stellata Bandy	Weches fm., Texas	Eocene
Lamarckina claibornensis Cushman	Weches fm., Texas	Eocene
Ceratobulimina cretacea Cushman and Harris	Campanian stage, Calif.	U. Cretaceous
Colomia californica Bandy	Campanian stage, Calif.	U. Cretaceous
C. californica var. mundula Bandy	Campanian stage, Calif.	U. Cretaceous
Höglundina supracretacea (ten Dam)	Campanian stage, Calif.	U. Cretaceous

[1] *Ceratobulimina limbata* Hussey (1949) is a junior synonym of *C. stellata* Bandy (1949). Both names were erected for this Gulf Coast species which has been erroneously placed in the European *C. eximia* (Rzehak) in many publications.

but a few were selected from Europe, Australia and South America. A total of about thirty-five samples were tested and none of the Foraminifera gave a positive test excepting those listed in table 1. An estimated 1,700 to 2,000 species of Foraminifera were thus tested. A few specimens of *Höglundina elegans* did not give a good reaction in a Miocene sample and it was omitted. This was the only case in which specimens of any of the species listed gave a negative test. An interesting variation in the reactions occurred in *Lamarckina claibornensis* wherein the dorsal surface gave a much better positive stain than the ventral side.

Those species which gave a positive reaction for aragonite are listed in table 1.

Mr. George Switzer of the Smithsonian Institution has corroborated the validity of the chemical reaction with X-ray studies in the case of *Colomia* and additional tests will be made.

In summary, it is apparent that (1) aragonite is quite stable in the tests of Foraminifera and in the shells of mollusks, (2) the cementing material in some arenaceous Foraminifera may prove to be aragonite and (3) there is no very close relationship between the genera represented by the aragonitic species in this study.

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THE ENERGY FACTOR IN SEDIMENTATION

W. D. KELLER
University of Missouri, Columbia, Missouri

ABSTRACT

Sedimentary rocks are the products which result from the interaction of energy and earth materials during weathering, transportation, deposition, and diagenesis. Energy which is transformed during the sedimentary process comes from the sun, the rotation of the earth, and to a smaller extent from the heat of the interior of the earth. The sedimentary process moves toward a decrease in free energy of the products from some reactions in its restricted system, but in other reactions the free energy of the products in the small system is increased. The formation of sedimentary rock-fuel illustrates the energy increase which is only a local and transitory upstream eddy in the overall, downstream flow of energy in the larger cosmic system.

The sedimentary process is merely an intermediate stage or response of the earth's surface materials in the transfer of energy from the sun and earth to outer space. A few geologic examples of the transformation of energy during weathering, transportation, deposition, and diagenesis are given to illustrate the interplay of energy and materials by which sedimentary rocks are formed.

INTRODUCTION

Sedimentary rocks may be described as the products which result from the response of earth materials to the energy impressed upon them within particular physical-chemical and biologic surroundings (environments) during the periods of weathering, transportation, deposition and diagenesis. The primary components of the sedimentary process are materials and energy, because when they are chosen the environment is automatically defined. The process may be symbolized as an equation:

$$\text{Source materials} \pm \text{Energy} = \text{Sedimentary rocks}$$

Geologists have traditionally given more of their attention to the materials factor, neglecting the energy factor. Actually, geologic processes operate only because of a flow of energy from a higher potential or intensity to one that is lower, and therefore energy is no less important than the materials in geologic work.

Indeed, all of the classically dominant processes of geology: gradation, vulcanism, metamorphism, and diastrophism, may be characterized in terms of energy operating on materials. Gradation is driven dominantly by energy from the sun and from the rotation of the earth. Vulcanism, metamorphism, and diastrophism are actuated primarily by the energy of primitive heat in the earth, radioactive heat generated within it, and the position of the material undergoing processing with respect to the centers of gravity and rotation of the earth. The position of a body or mass on the earth modifies its potential energy, which is a function of the excess of gravitational pull over centrifugal pull.

Transformation of energy is the common denominator to all geologic processes and reactions. It serves to coordinate them, despite their apparent diversity in kind and direction of movement. Geological science has been criticised as being an accumulation of distressingly numerous and relatively unrelated facts and empirical observations, and as being so piece-meal as to make for low efficiency in learning and teaching it. Perhaps an approach to it from the standpoint of energy flow may integrate some of the independent facts.

Moreover, the direction and rate by which a reaction or process operates are

functions of the energy which drives them. Knowledge of the energy which is available or involved may shed light on the conduct or tenure of the process. It is a potentially fruitful approach—not restricted to sedimentation—that invites further consideration by geologists. Geological literature is regretably scant in papers that relate process and energy. The purpose of this paper is to draw attention to a few relationships of energy to the sedimentary process. The paper is admittedly more superficial than desirable, insufficiently quantitative, and incomplete, but it is a beginning at least, and if it stimulates better thinking, along these lines, it will have served a good purpose.

The earth is a part of a vast system which includes the sun, the cold outer "empty" space, and other astronomical entities. This large system presumably undergoes a spontaneous decrease in free energy, an increase in entropy, and degradation in energy, as described by the second law of thermodynamics.

Many, probably most, geological processes move also in the direction of a decrease in free energy of the products. Over the very long-term view, it is expected that the net sum of all of them is in that direction, but locally in space and time there may be increases in free energy within parts of the geological system on the earth. This increase may be likened to small upstream eddies below a barrier within a stream whose overall flow is downward.

This local increase of energy in rocks derives from the position of the earth as a tiny barrier in the wide flow of energy from the sun to cold outer space. About one two-billionth of the sun's radiation lands on the earth (Ayres and Scarlott, p. 192). Although the universe, as we now know it, is moving toward a state of higher entropy, minor fluctuations in entropy occur on the earth which acts as an intermediary in the dispersal of solar energy. Indeed, the gradational process on the earth (so important to geolgists) can be shown to be merely a transitory, intermediate response in the dispersal of solar energy.

The earth acts somewhat like a heat engine, but a thermodynamically imcomplete heat engine, which operates on the energy it picks up from that flowing from the hot sun to cooler outer space. The source of the solar energy is attributed, of course, to the nuclear change wherein hydrogen goes to helium in the sun.

WEATHERING

It is convenient to begin with weathering as the first step in the formation of sedimentary rocks. Reiche (1945) has aptly defined weathering as, "the response of materials which were in equilibrium within the lithosphere to conditions at or near its contact with the atmosphere, the hydrosphere, and perhaps still more importantly the biosphere." It may be questioned whether the rock materials were truly in equilibrium within the lithosphere (for example a crystallizing basalt or granite, which is losing heat), but certainly the rocks are relatively more nearly at equilibrium within the lithosphere than later when they have been exposed at the earth's surface.

Mechanical Weathering.—Mechanical weathering, typified by granular disintegration and freezing and thawing, represents work done by solar energy. Rock absorbs heat from the sun during daytime and expands, whereby work is done. The rock gives off heat as night but does not return completely to its original volume. The pore space (Birch *et al.*, 1942, p. 28) which developed represents net work done. Water may be drawn into the capillary interstices by capillary action, and due to the heat of wetting the temperature may increase. If freezing of the pore water follows, with the loss of heat to the rock, atmosphere, and eventually to extra-terrestrial space, work is done in splitting the rock. The work of weathering is obviously merely an intermediary step in the transfer of energy from the sun to outer space. Much of the

sedimentary portion of the rock cycle and much of gradation in general depend for their operation upon this kind of energy transfer.

In order that this process should continue in operation, or that it should have operated in the same manner during the geologic past, it is important that the earth lose heat by radiation into outer space at a rate commensurate with the heat absorbed. An ideal black body absorbs and radiates heat at the same rates. The earth is not an ideal black body but it extracts work from incident solar radiation intermediate to its eventual reradiation. A state of dynamic equilibrium appears to prevail between the amount of heat absorbed and the heat reradiated from the earth, and therefore the mean annual temperature of the earth's surface shows no marked net increase or decrease over a short period of time (Birch, *et al.*, 1942, p. 270).

That such a dynamic equilibrium has existed during past geologic time is to be expected, but it is not expected that the same mean temperature of the earth's surface must have always existed. The albedo of the earth may be expected to have varied widely throughout geologic time, just as the albedo of the planets in our solar system varies from planet to planet. The absorption of solar heat by the earth would change if it was covered with chlorophyll-rich vegetation, ice, basalt, light-colored rocks, or water during wide-spread inundation. What part such change in heat absorption played in the variation of the temperature of the earth's surface is open to speculation, but the geological implications of it are noteworthy. The width and position of the belt on the earth where the temperature fluctuation is about 0°C, is particularly significant. Slight change in the mean temperature of the earth's surface might change not only the rate of weathering but also the type of weathering occurring at a given place. Atmospheric storms, climate, weather, and the work of the so-called physical agents in the entire gradational process would be modified vastly by a change in the balance of energy absorbed from the sun and reradiated by the earth. Its effect on the biosphere would be most significant.

Chemical Weathering.—The entire course of chemical weathering of rocks and minerals is essentially controlled by energy relationships. When chemical weathering is spontaneous, as it commonly is, it effects a decrease in the energy of the products. The weathering of marcasite and pyrite on spoil banks of coal mines is a striking example of energy release during the weathering reaction, especially if the heat evolved has raised the local temperature sufficient to ignite associated coal.

Less easily observed or measured is the oxidation of $FeSiO_3$, which is described below.

$$4FeSiO_3+O_2\rightarrow 2Fe_2O_3+4SiO_2-\Delta H$$
$$4\times 273.5=2\times 397+4\times 203-512$$

Heats of formation, in kilocalories, of the minerals from their constituent elements in standard state are given below the equation (Bichowsky and Rossini, 1936). In the reaction, 128 kcal. are liberated per mol of oxidizing $FeSiO_3$; weathering is usually an exothermic reaction (Van Hise, 1904).

Numerous specific examples of energy change in the weathering of minerals and rocks could be given, but instead a few generalizations are offered. Huggins and Sun (1946), and Ramberg (1952) have shown that the bonding energy of the silica group in silicates increases in the order neso-, soro-, ino-, phyllo-, to tectosilicates. Keller (1954), using data from Huggins and Sun (1946), has calculated the bonding energies of minerals in the Bowen reaction series. When the minerals are adjusted to 24 oxygen "cells," their energies range from 29,796 kcal. for forsterite, through 30,728 kcal. for augite, to 31,883 kcal. for hornblende, and 37,320 kcal. for quartz. Down the continuous series, the feldspars range from 31,935 kcal. for anorthite, through 34,335 kcal. for al-

bite, 34,266 kcal. for orthoclase, and 37,320 kcal. for quartz.

Hence, relatively more energy is released by the weathering of silicates on the neso-end, and they are the most susceptible to attack by the agents of weathering. On thermodynamic grounds, the tendency of weathering is to give rise to quartz which may be extrapolated as an end product of magmatic differentiation extended into the sedimentary domain. By the same tendency other simple oxides and carbonates are formed.

Weathering of primary silicates has been treated as a variation of ion exchange (Frederickson, 1951). Marshall (1953) and Graham (1953) have related quantitatively the power of a colloidal system to weather minerals by the bonding energy of exchange cations associated with clays and resins. To illustrate, H-Amberlite, which has a higher bonding energy for calcium ion than does H-humus, or H-kaolinite, was found to be more effective in weathering calcium phosphate minerals than H-humus or H-kaolinite (Graham, 1953). This quantitative measure of the weathering process in terms of energy relationships is most important.

Plant rootlets possess similar types of bonding energies for nutrient ions which they pull out of soil minerals, which are thereby weathered. Plants at different evolutionary levels have different intensities of bonding energies. The more primitive plants, like algae, attack even the freshest silicate rocks and pull away nutrient ions. The energy of the growing plant is utilized to implement its weathering attack on the minerals in contact with its roots (Keller and Frederickson, 1952).

In the foregoing discussion no mention has been made of the use of oxidation-reduction potentials, and the quantitative energy measurements obtainable from them. Students of sedimentation have lagged in applying this technique in their studies, although Zobell (1946), and later, Krumbein and Garrels (1952), have shown how the chemical energy or potential determines what minerals will be formed from the ions available.

TRANSPORTATION

The transportation of weathered material is usually downhill, towards the center of gravity of the earth. This means a decrease in potential energy and a decrease in capacity of the material to do work. For example, a pound of quartz and feldspar moved from the top of Pike's Peak to the delta of the Mississippi River loses about 14,000 foot-pounds of energy in the form of heat. The reduction to a peneplane of an ancestral mountain range transformed (degraded) the energy stored in its uplift into heat. Less academic but more strikingly evident, is the conversion of potential energy of rain water running off the mountain into hydroelectric energy which heats our homes, but the transformations of potential energy of water and rock moved downhill are the same. The source of energy for the mountain uplift is probably earth-derived, whereas the energy which lifted the water clearly came from the sun.

Downhill transportation means a loss in potential energy, but the upward movement of earth materials, in suspension or in solution, by the action of wind, ice, artesian water, or other agents, results in a temporary increase in their capacity to do work, or an increase in their free energy. It is recognized that this local increase in energy comes by the transformation of solar energy of higher intensity flowing to the earth. In the long run, it is expected that the addition of potential enrgy to earth materials will level off and, in consequence, no exception will be made to the second law of thermodynamics.

During transportation of detritus, clay is winnowed from sand in the atmosphere (Udden, 1914), and sorting occurs by washing in water, so that energy is put into the sedimentary system (Folk, 1951). The entropy of mixing is decreased. It is interesting to note that the high importance of this fundamental at-

tribute of sediments has been recognized recently by Wiliams, Turner, and Gilbert (1954) in their basic division in the classification of sandstones into wackes and arenites. The arenite is the recipient of more energy of sorting; it is the more mature of the two sandstone types.

The transportation of sedimentary materials is spontaneously in the direction of decrease in potential energy. If external sources contribute energy to a small part of the system, the small part may entrap some of this energy and thus realize an increase. Over the long term, the net result will be an increase in entropy and degradation of energy.

DEPOSITION

The deposition of coarse clastic sedimentary particles occurs when no further decrease in their potential energy with respect to gravity is possible, or if the energy available for further transportation of the particles is insufficient to overcome the frictional barrier. Colloids are flocculated and settle downward when the energies of Brownian movement and electrical charge are no longer able to maintain dispersion of the tiny fragments and hold them aloft. Neutralization of repulsive electrical charges (potentials) on the particles results in a decrease in energy. Oxidation of protective organic colloids, and dispersal of hydrated envelopes about the colloids, represent energy changes which implement flocculation.

The precipitation of soluble materials is spontaneous and usually occurs in the direction of decrease in energy of the precipitates. When evaporation of water leaves sedimentary deposits behind, energy (commonly solar) is put into the system. The solution and exsolution of CO_2 in water, so important in limestone deposition, are governed by the energies of temperature and pressure.

The flow of energy necessary for the formation of bioliths can be clearly defined. Photons furnish the energy to drive the photosynthesis process, and free energy is trapped and stored in the organisms and in the rocks they form, notably the caustobioliths. The heritage of energy from "fossil sunlight" in the fuels is so well known as to require no further comment (Ayres and Scarlott, 1952). The increase in free energy arising from the living organism, and the diverse courses by which such energy is transformed in accordance with the second law of thermodynamics is brilliantly described by Blum (1951). There are many ways in which release of the bio-energy may effect further sedimentational changes. For example, energy from the sun which has been incorporated in nitrogenous animal tissue may be released during the exothermic decomposition of the dead organism. Ammonia from the decay of the nitrogenous tissue may react in turn with calcium acid carbonate in solution and precipitate limestone. Under other circumstances, oxidized products may escape directly into the atmosphere.

Lest too great an emphasis be placed on energy to the exclusion of materials it may be repeated that the sedimentary rock which is formed is a result of the interplay of both materials and energy. Even though requisite energy is available the kind of sedimentary rock deposited depends upon the material available. Phantom members in cyclothem series result when either materials, energy, or both, are temporarily lacking. As another example, energy requirements permit almost any kind of sedimentary rock to be deposited along the coast of Florida today: but the abundance of sand in one place and mud at another, and the predominance of dissolved calcium carbonate or organic matter, determine the actual rock which is formed in any given place.

In the realm of sediments deposited from solution, the chemical potential plays the dominant role in the energy system. The influence of Eh, pH, and concentration on the rock which is deposited has been well introduced by Krumbein and Garrels (1952). The energy balance at various places within a

large basin may determine whether calcite, gypsum, dolomite, pyrite, goethite, or other non-clastic minerals will be deposited.

DIAGENESIS-CONSOLIDATION

The changes in a sedimentary rock during diagenesis may extend, obliterate, or even reverse some of the effects produced during prior stages in the rock's history. The extent to which diagenetic alteration develops is a function of the chemical potential of the solids and liquids, the temperature and heat, and the physical pressures which are available. Spontaneous changes are in the direction of a decrease in free energy, but it will be shown also that energy can be added to the rock system undergoing diagenesis.

The growth of coarser-grained minerals having lower vapor pressure from finer-grained particles results in a decrease in energy. Devitrification, and crystallization of minerals from an amorphous aggregate are generally exothermic. Recrystallization of minerals in accord with Rieke's principle decreases high potential (pressure) energy. The inversion of minerals like aragonite to calcite, and marcasite to pyrite, move toward conditions of higher stability and decrease in free energy.

Dewatering during the diagenesis of a sedimentary suspension and dehydration of moisture held more tenaciously (Hedberg, 1936) may require that energy (heat and/or high pressure) be put into the systems undergoing diagenesis. The work of compaction of the sediment is done by the descent of overlying beds which thereby transfer some of their potential energy to the sediment. Rising geothermal heat, coming, for example, from primitive heat or nuclear disintegration or radioactive minerals, may be transformed in part into crystal energy of the minerals growing during diagenesis.

Relic structure on the sub-crystallite level, and the energy implied by it in the growth of that structure, may be inherited within the course of further mineral transformation and growth. For example, degraded illite, that is, illite which has been leached of its constituent alkalies and alkaline earths but not sufficiently to transform it into new minerals (Grim, 1953, p. 352), may be converted to better-ordered micaceous minerals (such as illite, chloritic mica, and glauconite) without having to begin anew with dissolved ions and molecules. The skeleton structure and energy of illite have been inherited. It has been speculated (Keller, Westcott, and Bledsoe, 1954) that the formation of sedimentary diaspore might have occurred by condensation of a relic alumina octahedral sheet structure with energy inherited from pre-existing kaolinite which was desilicated during dialysis.

It seems logical that less energy change would be involved in mineral replacement if the structure of the antecedent mineral is passed on without serious modification to the replacing mineral than if synthesis of the latter begins with ions which are dispersed at random in solution. Looking at replacement solely from the viewpoint of energy, it is expected that the replacing mineral will be the one which can form out of the components available to the replacement system at a particular time so that the free energy of the products will be the lowest.

As the diagenetic process increases in intensity—somewhere in the transformation of sediments to solid rock or, perhaps, after bonefide solidification—it may grade into a stage of low-grade metamorphism. Where does diagenesis end, and metamorphism (the anamorphism of Van Hise (1904)) begin? Where does the change from calcareous mud to limestone end, and limestone to marble begin; where does the clay to shale transformation become a change from shale to phyllite (Hedberg, 1936)? Indicator minerals are used as arbitrary signs that metamorphism (anamorphism) has occurred. Van Hise believed that the reactions of anamorphism were largely endo-

thermic. It seems logical that the inception of anamorphism could be correlated ideally with the kind or degree of input of energy into the local rock system.

Energy stands in equal importance with materials in the formation of sedimentary rocks, and should receive equal consideration by geologists in their interpretation of all geologic processes. It has been neglected in past geologic thinking but this disregard should not be continued.

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